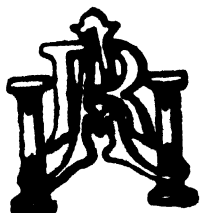


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METHODS USED IN PHYSICAL ANALYSES OF SOILS

Three years ago a group of soil scientists known to be interested in physical measurements in soils were asked to suggest a list of topics that might be covered in a special issue of SOIL SCIENCE on this subject. They were also requested to suggest the names of men who should be asked to contribute the necessary papers.

After an extended period of correspondence, the topics and the men to write the papers were agreed upon. Fortunately, every one of these men accepted his assignment, and we are now pleased to present the complete set of papers to the readers of the Journal.

Each of these papers has been prepared by a man who has had a great deal of experience in the field of measurement assigned to him. As a group, they constitute the best presentation of the techniques employed in soil physics that has been published. We believe the readers of SOIL SCIENCE will find themselves very much indebted to the authors for preparing these papers.

FIRMAN E. BEAR

PRACTICAL VALUES FROM PHYSICAL ANALYSES OF SOILS

L. D. BAVER

Hawaiian Sugar Planters' Association

The soil is a very complex environment for the growth of plants. From it, roots obtain mineral nutrients, water, and oxygen. The maximum productivity of the soil depends on the most favorable balance of these plant-growth factors. The utilization of nutrients is conditioned by air and water relationships, which are of a physical nature.

The soil must be handled in producing crops, manipulated in building roads and other earth structures, and given various treatments in its conservation. The handling or working of soils, therefore, is concerned with the physical behavior of the soil.

In any discussion of the practical values from analyses of the physical properties of soils, at least four phases of the problem must be treated. These involve: 1. Soil as a medium for plant growth. 2. Soil as a morphological unit. 3. Soil and water conservation. 4. Engineering aspects of soils.

SOIL AS A MEDIUM FOR PLANT GROWTH

Soil structure plays an important role in determining water and air relationships within the plant-root zone. From a practical point of view, a study of soil structure, particularly with respect to aggregation and porosity, aids in diagnosing and correcting troubles encountered in the growing of plants.

Manifestly, the water relationships of the soil depend on the amount and nature of the pores present: the water-holding capacity of the soil depends on the smaller pores; the drainage capacity, on the larger pores. Aeration, likewise, depends on

the larger pores. The soil environment, therefore, may be classified as good or bad, depending on its pore-space characteristics. In general, porosity is directly related to the amount and stability of the soil granules.

A good example of the use of physical analyses to diagnose a troubling condition and then to correct it may be found in the heavy clay soils of northwestern Ohio. When these soils were first cultivated, they produced abundant crops of corn and sugar beets. In time, farmers found that their crop yields were declining, irrespective of their methods of fertilization. They observed that the land drained less readily. It was much more of a task to prepare seedbeds and get good germination of seed. When dry weather came, the effects of the drought seemed more severe. Cracks developed in ever-increasing numbers. Plant diseases, particularly the root rots, were increasing in severity. In many instances, addition of commercial fertilizers resulted in no increases whatsoever. Corn was yielding 20 bushels an acre on old cultivated fields that should have been producing more than 70 bushels. Sugar beets were making 3 to 4 tons of beets an acre, when they should have been yielding 10 to 15 tons. Black root rot was wiping out about 50 per cent of many stands.

An analysis of the soil from the cultivated fields and from virgin areas showed some highly significant results. Early work by Bradfield (19) showed that the upper 3 feet of the cultivated soil contained 16 pounds more solid material per cubic foot than the virgin area. The total porosity of the cultivated soil had decreased about 17 per cent. Later investigations by Baver and Farnsworth (2) showed that the noncapillary porosity, or air capacity, of the cultivated soil was about 3.5 per cent by volume, whereas that of the same soil in good physical condition went as high as 25 per cent.

These data immediately suggested that the solution of the problem was to devise a system of management that would increase the air capacity of the soil. For corn, this involved the use of deep-rooted legumes, such as alfalfa and sweet clover, in the rotation. For sugar beets, the same legumes were used for soil improvement. In addition, the beets were planted in ridges to increase the porosity of the root zone. The results were phenomenal. Sugar beet yields were increased from a low of 1.5 tons an acre to more than 12 tons. The results in figure 1 indicate that after a yield of about 12 tons had been reached, corresponding to an air capacity of about 10 per cent by volume, something other than aeration was becoming the limiting factor. Despite the absence of any significant response from nitrogen fertilization on the regular plots, analysis of the beet leaves revealed that this element had become deficient.

One of the major effects of the better structural relationships was an almost complete disappearance of the black root rot disease in the young seedlings (fig. 2). Nearly 50 per cent of the beets were destroyed by black root rot when the air capacity of the soil was around 3 per cent. When the air capacity increased to about 10 per cent, the loss in stand was less than 10 per cent.

Corn yields at the Paulding County Experiment Farm jumped from an average yield of about 49 bushels in 1936 to a high of about 84 bushels in 1945 in an experiment to measure the effect of soil structure on production. The effects of the

rotations on corn yields are given in table 1. The yield of corn when all the residues were returned was only 27.3 bushels after 9 years as compared with 83.9 bushels for the 4-year rotation of corn-oats-alfalfa-alfalfa. It is significant that the corn yields on the continuous plots decreased nearly 50 per cent in 9 years

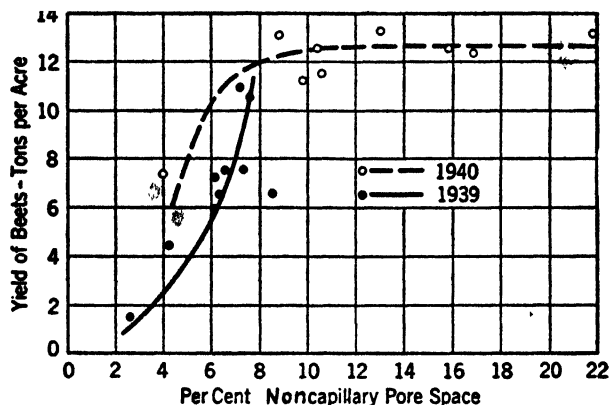


FIG. 1. RELATION OF SOIL POROSITY TO SUGAR BEET FIELDS

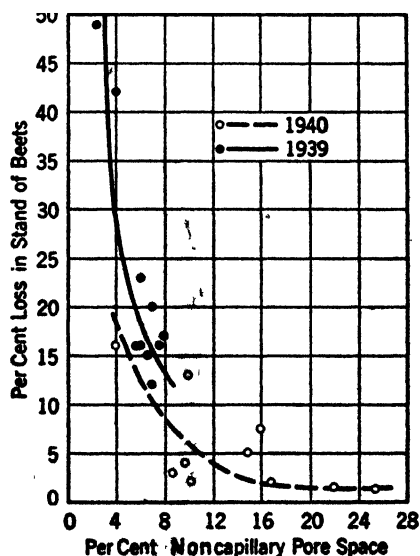


FIG. 2. RELATION OF SOIL POROSITY TO STAND OF SUGAR BEETS

while those from the best rotation increased more than 70 per cent over the average yield in 1936. Detailed studies by Page and Willard (16) on the relation of the physical properties of the soil to yields show rather definitely that as the aggregation of the soil and its air capacity were increased by the rotations, corn production increased correspondingly. The relationship of soil structure to corn

yields is illustrated in figures 3 and 4. Although the variations in sampling prevent an exact mathematical relationship between yield and air capacity or aggregation, the trends are very significant. Low air capacities and low states of

TABLE 1
Effect of rotations on corn yields

ROTATION	YIELD OF CORN		
	1936	1945	
	bu./A.	bu./A.	per cent*
Corn, oats, alfalfa, alfalfa.....	42.8	83.9	171
Corn, oats, alfalfa.....	50.0	78.7	160
Corn, oats, residues returned.....	61.5	54.0	110
Corn, residues returned.....	50.4	27.3	56

* Of 1936 yield.

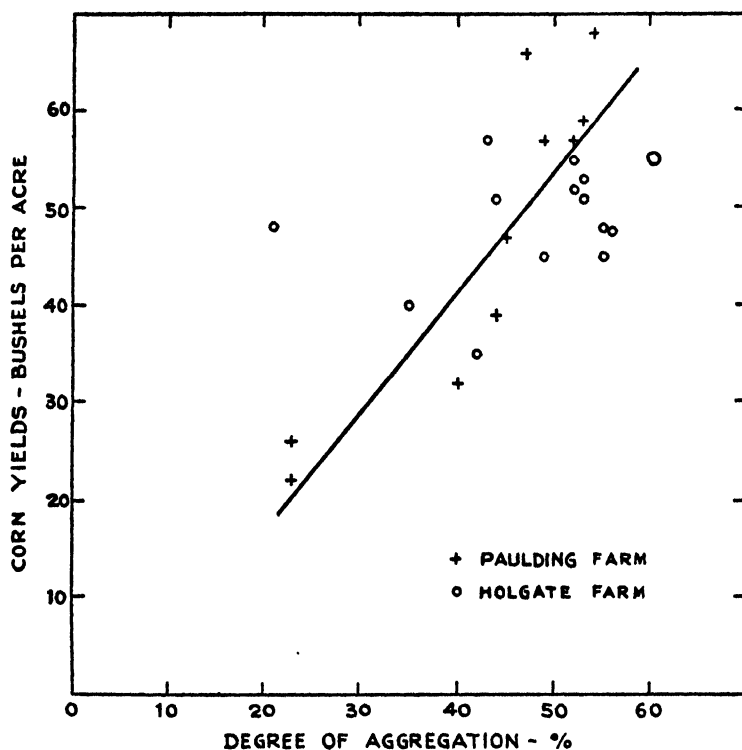


FIG. 3. RELATION OF CORN YIELDS TO SOIL AGGREGATION

aggregation give low yields. Differences in the drainage and mechanical handling characteristics of the different plots were quite obvious in the field.

There are numerous researches in the literature showing the effect of certain cropping and soil management practices upon the changes in the physical prop-

erties of the soil. These studies provide evidence of the beneficial or detrimental effects of a given practice upon the soil. From such results, one can deduce what will probably happen to crop yields.

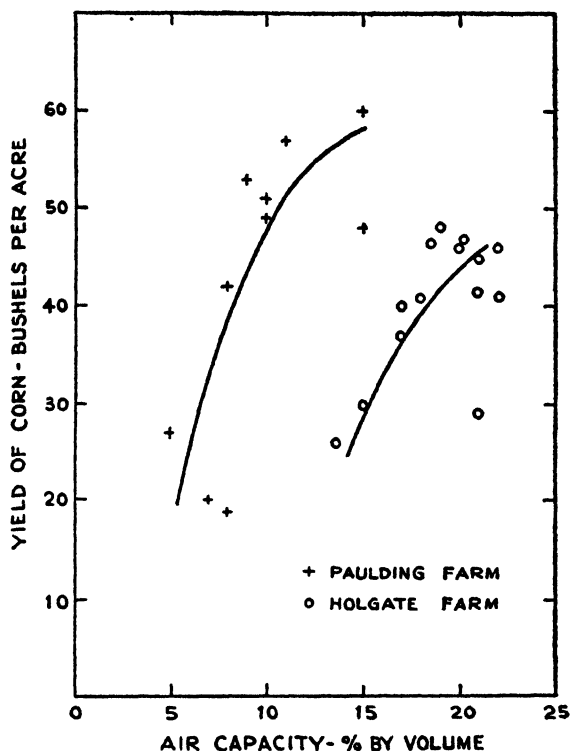


FIG. 4. RELATION OF CORN YIELDS TO SOIL AERATION

SOIL MORPHOLOGY

Studies in soil genesis and classification must of necessity take into consideration such physical properties of the soil as the distribution of various-sized particles throughout the profile, the consistency and structure of the various horizons, and the mineralogical composition of the different layers.

The importance of an analysis of the distribution of clay throughout the soil profile as an aid in soil classification is shown in figure 5. These data, taken from studies of Riecken (18) in Iowa, show that Marion silt loam has undergone considerable profile development with a large amount of eluviation into the B horizon. Fayette silt loam, on the other hand, has only a slight clay accumulation in the B horizon. Both soils have developed under forest vegetation. The differences in the profile characteristics, as brought out by physical analyses, not only help in differentiating between the two pedologically but also aid in characterizing their differences agriculturally.

Another example of profile characteristics that illustrate differences between

two adjacent soils is shown in figure 6. Marshall silt loam exhibits a uniform porosity and air capacity throughout the entire profile. In Shelby loam, the maximum porosity occurs in the upper 12 inches. The pore space of the Mar-

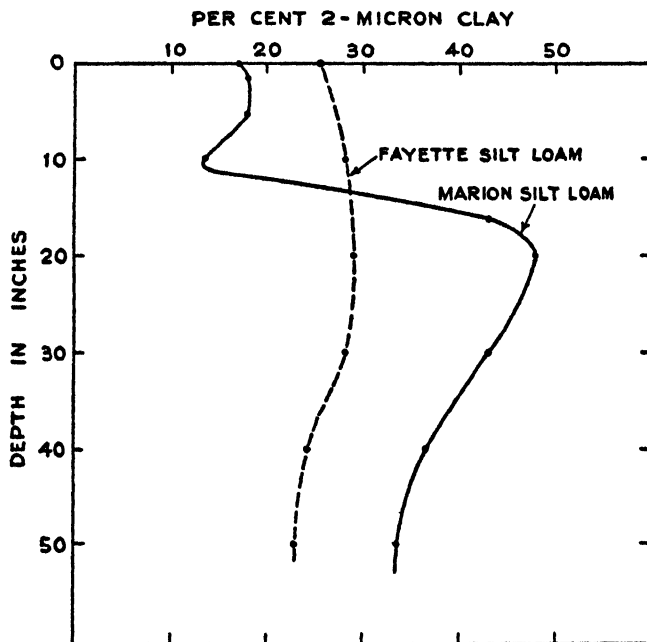


FIG. 5. CLAY CONTENT OF TWO FOREST SOIL PROFILES

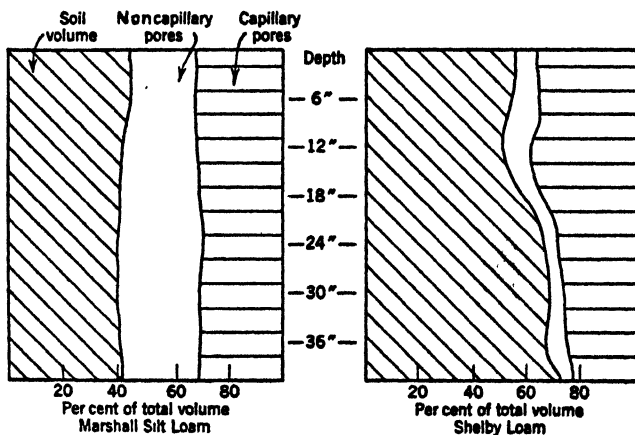


FIG. 6. VOLUME RELATIONSHIPS IN MARSHALL SILT LOAM AND SHELBY LOAM PROFILES

shall is about equally divided between large, noncapillary pores and smaller capillary ones. This provides good drainage and aeration as well as a favorable water-holding capacity. The Shelby, on the other hand, has a very small non-

capillary pore-space content in all horizons. It is almost impermeable to water, droughty during extended periods of insufficient rainfall, and otherwise less productive as an agricultural soil than the Marshall.

Physical analyses of soils as shown in figures 5 and 6 should be made of all soil profiles, supplementary to their final classification. This is true for both productivity ratings and pedological characterizations.

Bendixen, Hershberger, and Slater (3) have suggested that soils can be grouped according to their permeabilities. They showed that the percolation rates of four soil profiles from northwestern Ohio appear to be about the same function of pore space. Seven Coastal Plain soil profiles comprise a different group with respect to permeability. The correlation between pore space and percolation rates of the profiles holds even though the soils vary widely in textural composition. These workers found that the pore-space classification of permeability developed from the data for Coastal Plain soils was in practical agreement with the field classification of Missouri soils.

Marshall and Haseman (11) have applied analyses of heavy minerals in a study of the weathering and development of soil profiles. Using Grundy silt loam as an example, they found that the present profile was heavier than the original parent material, partly because of oxidation and hydration of minerals that led to clay formation. Mineral breakdown was vigorous in the 0-22-inch layers.

These few examples indicate the practical value of physical analyses to the student of soil classification as well as to the individual who recommends land use on the basis of soil characteristics.

SOIL AND WATER CONSERVATION

Water conservation includes the saving of precipitated water from excessive runoff, the drainage of soils, and the irrigation of land that has deficient rainfall.

Water infiltration and retention

Let us first consider the practical aspects of physical analyses in the control of excessive runoff and accompanying loss of soil as erosion. The most important factor in saving precipitated water from any given rainfall relates to the ability of the soil to take in the rain as it falls. The water infiltrated into the soil during rainfall may either be held in the small pores of the upper horizons, where it can be used by plant growth, or it may find its way by percolation to underground storage reservoirs or emerge in streams as stream flow. From a hydrological point of view, the condition of the soil surface, the permeability of the profile, and the moisture content of the soil at the time of precipitation are the important physical properties that must be known to evaluate water infiltration and retention.

Hursh and Hoover (9) in their hydrologic studies in the southern Appalachians emphasized the importance of soil profile characteristics as follows:

For the purpose of describing hydrologic characteristics, structure, porosity, and the extent of biological pathways for water appear to be of the first importance. In terms of soil hydrology, complete profile description should furnish a measure of the total volume, size, shape, and continuity of the pore spaces within each soil horizon. It should provide

an index of the infiltration and transmission rate of water through each horizon. Finally, it should indicate the amount of moisture already present, and the amount of storage opportunity remaining.

By simple drainage technics, they were able to measure detention and retention storage in the soil profile, both of which are functions of porosity. Their work, and that of Horton (8), illustrates the value of physical data in hydrology.

One of the best examples of differences in soil infiltration capacities as they relate to practical differences in agricultural behavior is the work of Musgrave (12) on Marshall silt loam and Shelby loam. His data are illustrated in figure 7, which shows that the Marshall profile is able to handle 7.8 times more water per hour than the Shelby. Runoff on the Marshall could be prevented by any treat-

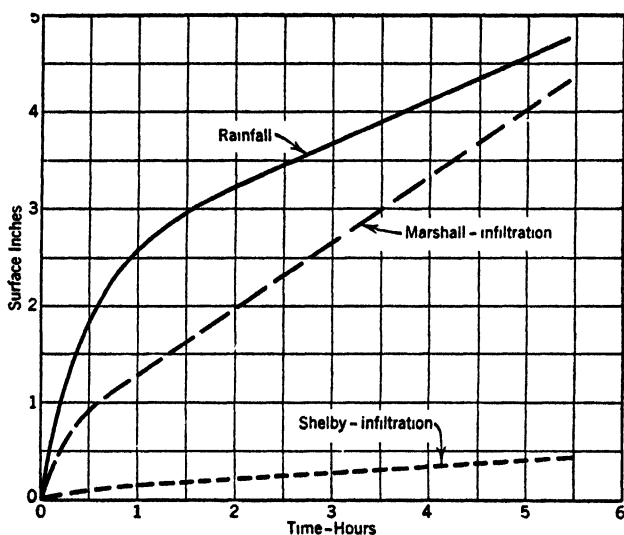


FIG. 7. INFILTRATION CURVES OF MARSHALL SILT LOAM AND SHELBY LOAM

ment that would impound about 1.25 inches of water. On the other hand, the Shelby profile is so impermeable that there is no practical way to prevent runoff when it is being farmed. It is worthwhile to note that Musgrave's measurements have been confirmed in the field, where the ratio of runoff of the Shelby to the Marshall was about 7. The reasons for the differences between these two soils are evident from their pore-space relationships (fig. 6): Marshall silt loam has about five times the volume of noncapillary pores as Shelby loam.

The amount of water passing into and through the profile is determined by the permeability of the least permeable horizon. If this layer is at the immediate surface, the infiltration rate of the soil is limited by how fast the water can enter the surface. The hydrology of the entire profile is conditioned by the surface in this instance. All practical measures that tend to improve the structure of the immediate surface will directly benefit water infiltration and conservation.

One of the important factors in the practical interpretation of climatological

data in terms of water runoff and storage within a watershed is the amount of water that is in the "soil reservoir" when the rain falls. This problem has as yet not been entirely solved because of inadequate methods for determining moisture in the soil *in situ*. Attempts to classify rains on the basis of the length of time between precipitations have given some practical leads, but they have been far from satisfactory. Neal (14) found that the soil-moisture content at the beginning of the rain had a greater effect than any other factor upon the rate of infiltration for the first 20 minutes. Obviously, continuous records of soil moistures will be of great practical value in all hydrological studies.

The physical properties of the soil exert an appreciable influence on soil losses during runoff. Soils with a high content of water-stable aggregates will resist the dispersive action of rain-drops. This will retard erosion considerably. Ellison (6) has demonstrated that particles must be detached before they can be transported. Physical analyses that indicate the relative degrees of dispersion of soils provide valuable information on practical soil management for erosion control.

Drainage of soils

Soils are drained to remove excess water from the pores and permit adequate aeration for the plant-root zone. Central Europeans use particle size as a guide to the depth and spacing of drains to effect water removal. Aronovici (1), working on soils of the Imperial Valley in California, has shown that pore-size distribution is a function of texture. He obtained an excellent correlation between the coefficient of permeability and the percentage of silt plus clay. The accuracy of the correlations obtained is adequate for field application in laying out drainage systems. Neal (13) used the tension-free pore space, as calculated from the moisture equivalent, to estimate the correct depth and space of tile drains in Minnesota soils. It is important to emphasize that texture alone may be used to estimate pore-space relationships when the soil is primarily sandy or silty in character. In compacted soils, as well as in those containing a large amount of clay, it is necessary to evaluate the pore-space situation by means other than texture. Granulation and structure play significant roles in such soils.

The author found differences in the drainage of soils along the Ulua River in Honduras where one soil grew good bananas and the other a very poor crop. Texture, consistency, and fertility were practically identical. Porosity determinations revealed the true differences between these soils. The better-drained soil had an air capacity, or noncapillary porosity, of 8.1 and 5.9 per cent at depths of 0-16 and 16-30 inches, respectively. The poorly drained soil had values of 5 and 2 per cent for the same depths.

Any successful system of field drainage must take into account the physical properties of the soil. Many tile drains installed without regard to soil properties fail to discharge water because the soil is too impermeable. If the profile characteristics of the soil are favorable to subsurface drainage, tile drains are indicated. If the profile has characteristics that indicate little or no vertical movement of water, a system of surface drainage to handle the excess water must be devised.

In addition to knowledge of the structure of the profile, information on water

flow within the soil is valuable. This may be obtained through correct installation of tensiometers at various depths.

Irrigation

Irrigation problems involve not only the question of when to apply water and how much to put on, but also factors affecting the ease of penetration and distribution of water throughout the soil. The former concerns itself with soil moisture contents and wilting points of plants. The latter is affected by several physical properties of the soil.

Researches on the relationship of plant wilting to soil moisture have been numerous. Such terms as *wilting percentage*, *field capacity*, and *moisture equivalent* are associated with irrigation problems. The search for methods of measuring moisture deficits in the soil has proceeded at a rapid pace. After the wilting percentage of the soil has been determined by either direct or indirect methods, the amount of water available to the plant has been measured or estimated by taking soil samples and determining the moisture present, by using weather data to estimate the drying out of the soil, and by installing porous cones in the soil and weighing them, to mention the more important approaches.

Recently, renewed emphasis has been placed on electrical methods for measuring moisture in soils. The Bouyoucos gypsum block (4), the Colman fiber-glass unit (5), the electrothermal method, and others have been developed which offer considerable promise of furnishing a running account of the moisture status of the soil at different depths as a basis for irrigation. Methods based on electrical conductivity are affected by salts in the soil solution or the irrigation waters. The electrothermal method, although not affected by salts, has not yet been perfected for field usage.

The tensiometer (17) is being used rather widely to measure moisture changes in the soil as a basis for irrigation practice in the field. Unfortunately, these tensiometers cannot be placed in the root zone of the plant because they become ineffective when the soil-moisture tension approaches 1 atmosphere, which is approximately field capacity. They must be placed at lower depths in the soil and the irrigation of the surface layers gauged upon the water status of the lower horizons. Despite this apparent weakness, however, the tensiometer can serve a real purpose in irrigation control.

The problem of water penetration and absorption is rather acute on certain soils. For example, Jamison (10) has reported that irrigation of porous sandy soils in the citrus groves of Florida is impeded by resistance of the surface soil to wetting. The soil on one of the plantations in Hawaii has such a slow rate of penetration that the rate of irrigation must be decreased considerably below that of other soils. When some soils become wet they slake and seal at the surface, thereby preventing water penetration. Other soils are so porous and shallow that the correct water usage must be based on the water-holding capacity of the root zone. Movement of water either laterally or vertically varies from soil to soil depending on pore-space and tension relationships. These are all practical problems in the use of water for irrigation, where efficient production of crops is paramount. They can only be solved by an understanding of the soil.

ENGINEERING ASPECTS OF SOILS

Whenever soils are manipulated, different physical factors come into play. Obviously, physical analyses are of considerable practical importance in developing sound principles for handling soils from the engineering point of view. Only a few of the fields in which engineering depends on soil data are treated here.

Terracing and contouring for erosion control

Terracing and contouring aim to change the slope characteristics of the land so that the amount and velocity of runoff are decreased to the point where a minimum of soil loss occurs. Depending on the nature of the soil, water is conserved by permitting greater infiltration as a result of the reduced velocity of the runoff. Although terrace spacing is determined primarily by the slope of the land, the ability of soil to absorb and transmit water through the profile must also be considered. An excellent example of the value of putting soil properties to work in planning the terracing of land may be found in a comparison of the results of experiments at the Soil and Water Conservation Stations at Clarinda, Iowa, and Bethany, Missouri. The former is on permeable Marshall silt loam. The latter is on impermeable Shelby loam. Original experiments were laid out primarily upon the consideration of the degree and length of slope and with little recognition of soil properties. As a result, the terraces on Marshall silt loam were too close together, and there was little or no runoff from them. The system had to be redesigned to give a more practical farming layout. For example, it was found that with a vertical spacing of 6 feet on a 9 per cent slope less than 0.2 per cent of the annual rainfall left the field as runoff. The usual recommendation for this type of slope is a terrace interval of 4 to 5 feet. Though the engineers erred in the direction of too close spacing on this permeable soil, it is possible that closer spacing may be necessary on more impermeable soils to ensure adequate handling of the water.

Level terraces have been recommended in a number of cases for the conservation of rainfall, especially in areas of limited precipitation. This practice becomes rather dangerous on soils of low permeabilities. Water stands in the terrace channel and causes all vegetation to be drowned. Wilson, Riecken, and Browning (20), who studied profile characteristics of Iowa soils with regard to level terraces, have drawn the following conclusions from their findings:

Level terraces, to operate satisfactorily, require high permeability at the soil surface and throughout the profile and a storage capacity for a 3- to 4-inch rain. This represents a storage capacity requirement of about 10 inches for the soil area immediately under the storage channel. Unless these requirements are met, there is danger of overtopping of the terrace or of water standing in the channel to drown out the crop.

They found that such physical measurements as noncapillary porosity, permeability, mechanical analyses, and dispersion ratios aided in obtaining information that could be used "as a basis for a better understanding of soils and crop problems and for making sound land use recommendations."

Since contour farming is essentially a system in which a large number of small terraces are placed around the slope, it necessarily follows that the same state-

ments made in conjunction with terracing apply here. Data from the Soil and Water Conservation Stations indicate that contouring is more successful on more permeable soils than on less permeable ones.

Tillage practices

The classical work of Nichols (15) at the Alabama Agricultural Experiment Station has shown that the passage of tillage implements through the soil is affected by a number of physical factors, which must be taken into consideration in the design of the plow and other tillage machinery. These so-called "dynamic factors" are compression, shear, adhesion, and cohesion. The sum total of their effects is translated into the force necessary to pull the implement through

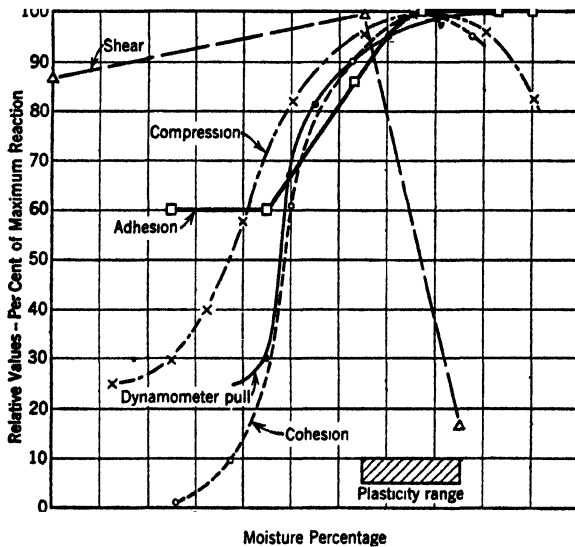


FIG. 8. RELATION OF DYNAMIC PROPERTIES TO PLASTICITY OF SOIL

the soil. Such soil properties as particle size, colloid content, moisture, porosity, organic matter, and consistency all play a part in determining the behavior of a given soil. When the dynamic properties of soils involved in tillage are correlated with soil plasticity, information is provided that enables the engineer to base machine design upon soil properties. These correlations are shown in figure 8. Compression increases with moisture content to a maximum within the plasticity range. This is true also for cohesion. The shear value of soils reaches its maximum at the lower plastic limit. Maximum adhesion between soil and metal occurs at the upper plastic limit. The force required to pull an implement through soil reaches its maximum slightly above the lower plastic limit.

These relationships also have considerable importance in other areas of engineering, particularly in the stabilization of soils. They indicate the practical value of soil physics in the solution of engineering problems.

Soil stabilization

Soil stabilization is a relatively new term used in highway construction and other engineering projects dealing with soils. It has a rather broad meaning and includes the use of chemical, physical, or other methods for improving soils for engineering purposes. Soil stabilization may be achieved by:

1. Addition of granular material to a silt or clay soil to improve the supporting power of the soil.
2. Densification, by physical means, of the soil already in place.
3. Addition of portland cement to the soil or the soil-aggregate system to produce a hardening effect.
4. Use of bituminous materials as an admixture for both binding and waterproofing.
5. Use of chemicals and resins for both waterproofing and binding.

Use of any of these methods for soil stabilization requires a thorough knowledge of the physical and mechanical properties of each soil that is handled and the measurement of these properties by accepted methods. It has been shown (21), for example, that the nature of the ion on the surface of the clay particles, as well as the mineralogical nature of the clay itself, exerts important effects upon the stabilization of soils by use of cement, resins, bitumens, and chemicals. Likewise, the nature of the ion affects the hydration properties of the soil, which in turn influences densification. The mere addition of warm water to a soil fill will permit closer compaction of the soil than will moistening with cold water. The hydration of the clay particles is smaller, the higher the temperature.

The engineers have established a classification of soils for engineering purposes. In addition to mechanical analyses of the road material, the following physical analyses are used:

1. Moisture equivalent to provide information on capillarity, permeability, and compressibility.
2. Plasticity number or index to evaluate cohesion.
3. Lower plastic limit to determine the capillary capacity of a manipulated soil.
4. Shrinkage and swelling to ascertain the combined effects of resistance to consolidation, cohesion, and capillarity.

Numerous other tests are made to determine the effects of soil stabilization materials. These include slaking, porosity or the number of voids, rate of compression, shearing strength, and crushing strength (7). Obviously, greater use of soil physical analyses generally in the engineering field may be expected in the future. Chemical soil stabilization received great impetus during the second world war. Its use requires careful physical checks and controls.

SUMMARY

Physical analysis of soils are finding greater practical application in agriculture and engineering. Research workers in both fields are learning that a practical knowledge of soil physics is essential not only for diagnosing the problem at hand but also for finding its solution.

REFERENCES

- (1) ARONOVICI, V. S. 1947 The mechanical analysis as an index of subsoil permeability. *Soil Sci. Soc. Amer. Proc.* (1946) 11: 137-144.
- (2) BAVER, L. D., AND FARNSWORTH, R. B. 1941 Soil structure effects in the growth of sugar beets. *Soil Sci. Soc. Amer. Proc.* (1940) 5: 45-48.
- (3) BENDIXEN, T. W., HERSHBERGER, M. F., AND SLATER, C. S. 1948 A basis for classifying soil permeabilities. *Jour. Agr. Res.* 77: 157-168.
- (4) BOUYOUCOS, G. J., AND MICK, A. H. 1940 An electrical resistance method for the continuous measurement of soil moisture under field conditions. *Mich. Agr. Exp. Sta. Tech. Bul.* 172.
- (5) COLMAN, E. A. 1946 The place of electrical soil-moisture meters in hydrologic research. *Trans. Amer. Geophys. Union* 27: 847-853.
- (6) ELLISON, W. C. 1945 Some effects of rain drops and surface-flow on soil erosion and infiltration. *Trans. Ann. Meeting Amer. Geophys. Union* 26 (pt. 3): 415-429.
- (7) HOGENTGLER, C. A. 1937 Engineering Properties of Soil. McGraw-Hill Book Co., New York.
- (8) HORTON, R. E. 1933 The role of infiltration in the hydrologic cycle. *Trans. Ann. Meeting, Amer. Geophys. Union* 14: 446-460.
- (9) HURSH, C. R., AND HOOVER, M. D. 1942 Soil profile characteristics pertinent to hydrologic studies in the southern Appalachians. *Soil Sci. Soc. Amer. Proc.* (1941) 6: 414-421.
- (10) JAMISON, V. C. 1947 Resistance to wetting in the surface of sandy soils under citrus trees in central Florida and its effect upon penetration and efficiency of irrigation. *Soil Sci. Soc. Amer. Proc.* (1946) 11: 103-109.
- (11) MARSHALL, C. E., AND HASEMAN, J. F. 1943 The quantitative evaluation of soil formation and development by heavy mineral studies: a Grundy silt loam profile. *Soil Sci. Soc. Amer. Proc.* (1942) 7: 448-453.
- (12) MUSGRAVE, G. W. 1935 The infiltration capacity of soils in relation to the control of surface runoff and erosion. *Jour. Amer. Soc. Agron.* 27: 336-345.
- (13) NEAL, J. H. 1934. Spacing and depths of tile drains. *Agr. Engin.* 15: 229-232.
- (14) NEAL, J. H. 1937 The effect of the degree of slope and rainfall characteristics on runoff and soil erosion. *Missouri Agr. Exp. Sta. Res. Bul.* 280.
- (15) NICHOLS, M. L. 1929, Methods of research in soil dynamics as applied to implement design. *Ala. Agr. Exp. Sta. Bul.* 229.
- (16) PAGE, J. B., AND WILLARD, C. J. 1947 Cropping systems and soil properties. *Soil Sci. Soc. Amer. Proc.* (1946) 11: 81-88.
- (17) RICHARDS, L. A., AND NEAL, O. R. 1937, 1938 Some field observations with tensiometers. *Soil Sci. Soc. Amer. Proc.* (1936) 1: 71-91; (1937) 2: 35-44, 55-64.
- (18) RIECKEN, F. F. 1946 Selection of criteria for the classification of certain soil types of Iowa into great soil groups. *Soil Sci. Soc. Amer. Proc.* (1945) 10: 319-325.
- (19) SALTER, R. M., LEWIS, R. D., AND SLIPHER, J. A. 1938 Our heritage—the soil. *Ohio Agr. Ext. Serv. Bul.* 175.
- (20) WILSON, H. A., RIECKEN, F. F., AND BROWNING, G. M. 1947 Soil profile characteristics in relation to drainage and level terraces. *Soil Sci. Soc. Amer. Proc.* (1946) 11: 110-118.
- (21) WINTERKORN, H. F. 1936 Surface-chemical factors influencing the engineering properties of soils. *Proc. Ann. Meeting Highway Res. Bd.* 16: 293-308.

METHODS OF MAKING MECHANICAL ANALYSES OF SOILS

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Mechanical analysis yields fundamental data that are indispensable to the proper study of the classification, morphology, and genesis of soils. By means of mechanical analysis the particle-size distribution is placed on a quantitative basis. The accumulation or loss of clay from soil horizons is made more apparent, and determination of the relationship of parent material to the solum is greatly facilitated. Information regarding the physical properties of soils and related to permeability, water retention, plasticity, aeration, base-exchange capacity, and tillage is obtained. To the engineer, particle-size distribution data serve as one criterion for studying the rate of siltation of waterways and harbors and for determining the suitability of soil materials for construction purposes.

TABLE 1
Classifications of soil separates

U.S.D.A. CLASSIFICATION		INTERNATIONAL CLASSIFICATION	
Conventional names	Diameter	Fraction	Diameter
	mm.		mm.
Very coarse sand*	2.0 -1.0	I	2.0-0.2
Coarse sand..	1.0 -0.5		
Medium sand .	0.5 -0.25		
Fine sand....	0.25-0.1	II	0.2-0.02
Very fine sand. .	0.1 -0.05		
Silt.	0.05-0.002	III	0.02-0.002
Clay.	<0.002	IV	<0.002

* The term "very coarse sand" for soil particles 1 to 2 mm. in diameter was recently adopted by the Division of Soil Survey.

A number of schemes have been proposed for classifying soil separates on a size basis, but only two, the Atterberg or International system and the U. S. Department of Agriculture system, are in general use among soil scientists. Table 1 shows the two systems of classification.

Previous to 1938, the U. S. Department of Agriculture classification designated particles 0.05 mm. to 0.005 mm. *silt*, and less than 0.005 mm. *clay*. Osborne, the author of this classification, employed these size limits largely because of convenience in relation to the micrometer scale (13). During the period 1928 to 1938 an additional determination was made of the material less than 2 μ . This material was designated *colloid*. The 5- μ limit for clay was objectionable because the coarser portion included primary minerals (24). To conform to the more general international usage and to include some of the coarser material in the silt fraction, the upper size limit for clay was lowered to 2 μ . The U. S. Department of Agriculture system makes possible a more detailed classification

of soils because the greater number of sand separates facilitates subdivision into several intermediate textural classes. Both the U. S. Department of Agriculture and the International systems of classification are used in reporting results obtained in this laboratory.

DISPERSION

An accurate mechanical analysis is dependent on complete dispersion of the soil sample. For mechanical analysis, the aggregates in a properly dispersed sample should not be larger than the upper limit of the smallest sized fraction to be determined. The sample must remain dispersed during the course of the analysis. Dispersion is brought about by removal of any cementing agents such as organic matter and free iron oxide, removal of flocculating ions such as calcium, mechanical agitation, and use of dispersing agents.

Acid treatment

In the International method of analysis the soil is treated with enough HCl to decompose the carbonates and still leave 250 ml. of solution of 0.2 *N* HCl. In addition to removing the carbonates and eliminating their cementing effect, HCl treatment removes the exchangeable bases and soluble salts, which might later interfere with dispersion. That such treatment may be unnecessary and even objectionable for calcareous soils has been pointed out by Bodman (5), Hilgard (12), and Olmstead, Alexander, and Middleton (18). The principal objection to the acid treatment is that particles of limestone, dolomite, and precipitated carbonate are removed and, where large amounts of these materials are present, the textural classification of the soil may be considerably altered.

Whether the soil should be pretreated with hydrochloric acid depends upon the object of the analysis, the nature of the soil, and the dispersing agent employed. Olmstead *et al.* (18) have shown that ammonium and sodium hydroxides are not suitable for dispersing soils high in exchangeable bases when acid pretreatment is omitted. When sodium oxalate was used, a stable dispersion was obtained even with calcareous soils. They, therefore, suggested the use of sodium oxalate as a dispersing agent and omitted the HCl treatment in their method.

Removal of organic matter

Robinson (21) was among the first to show the effect of soil organic matter on degree of dispersion. He obtained as much as a fourfold increase in the percentage of clay after treatment of soils with H_2O_2 . This effect was attributed to the removal of material acting as a cementing agent between the particles. Baver (2) reported similar results with Ohio soils, although the increase in the percentage of clay was not so great as that obtained by Robinson. Beale concluded that H_2O_2 treatment could be omitted for routine analysis of most lateritic soils (4). The organic content of the soils that he studied ranged from 0.33 to 2.62 per cent. Winters and Harland (26) concluded that with Illinois soils there was no advantage to the hydrogen peroxide treatment if the sample was washed with HCl.

It is evident that the effect of organic matter on the degree of dispersion varies widely with different soils and depends on the amount and kind of clay and organic matter present and the subsequent treatment employed. In this laboratory, because of the diverse nature of soils received for analysis, treatment of samples with H_2O_2 prior to mechanical analysis is considered a necessity. Such treatment reduces the number of erratic results due to incomplete dispersion and eliminates organic matter as a weight factor in the pipetted samples.

Mechanical dispersion

Soil aggregates are usually broken up by rubbing, boiling, shaking, or mechanical stirring, the object being to slake without undue grinding of discrete particles. For complete dispersion, the First Commission of the International Society of Soil Science recommended treatment with H_2O_2 followed by addition of HCl and then either stirring and decanting with 0.1 N ammonia, or shaking with 10 per cent ammonium hydroxide if the pipette method was employed.

Dispersion by means of a high-speed stirrer was developed by Bouyoucos (6). In his method the sample is allowed to soak for 15 minutes and then stirred for 5 minutes if the soil is a sand; heavier-textured soils are stirred for 10 minutes. Other workers have modified the Bouyoucos procedure and recommend a soaking period of at least 18 hours followed by a stirring period of 1 minute (11).

Mechanical shaking with a dispersing agent is convenient and effective. Winters and Harland (26) obtained maximum dispersion on some Illinois soils by shaking with sodium carbonate for 48 hours. They suggested that the greater effectiveness of the longer shaking period might be related to the rate of hydration. In general, shaking the sample overnight suffices.

Dispersing agents

Maintenance of a stable dispersion depends on complete hydration of the clay particles together with establishment of a high negative potential by addition of a suitable peptizing agent. The more common dispersing agents that are or have been employed in the mechanical analysis of soils are ammonium hydroxide, sodium hydroxide, sodium carbonate, sodium silicate, sodium oxalate, and sodium hexametaphosphate. Ammonium hydroxide was widely used among earlier investigators because it had the advantage of being easily removed by drying. Alexander (1) used sodium hydroxide for dispersing lateritic soils high in sesquioxides and low in exchangeable bases. More recently Tyner (25) reported the use of sodium hexametaphosphate as a deflocculating agent. He obtained complete dispersion on a wide variety of soils that included calcareous and gypseous soils. [The effectiveness of sodium hexametaphosphate is due to the formation of a calcium metaphosphate complex. Since this complex remains undissociated, the activity of the calcium in solution is eliminated. Subsequent work in this laboratory also indicated the superiority of sodium hexametaphosphate as a dispersing agent.] It has been used by us almost exclusively for the last 8 years.

It is apparent that no one method of dispersion is applicable to all soils, and suitable modifications must be made when special cases are encountered.

METHODS OF MECHANICAL ANALYSIS

After dispersion of the sample, the soil particles may be separated into the desired size classes by techniques employing sieving, elutriation, centrifugation, or simple sedimentation. The last three methods are based on the fact that a sphere attains a constant fall velocity in a settling medium, provided the sphere is large enough to be unaffected by Brownian movement and the rate of fall is influenced solely by the viscosity of the medium. The terminal fall velocity of a sphere is expressed by Stokes' law:

$$V = \frac{2}{9} g \frac{(d - d')}{n} r^2$$

where V is the velocity of fall in cm./second; g is the acceleration due to gravity or centrifugal force; d is the density of particle in gm./cc.; d' is the density of fluid in gm./cc.; r is the radius of sphere in cm.; n is the dynamic (absolute) viscosity of the fluid in dyne-seconds/sq. cm.

Elutriation

Elutriation methods depend upon rising currents of water of different velocities to grade the particles according to their settling velocities. The finer material is borne to the top of the elutriator while the coarser particles settle to the bottom. One of the earliest elutriators was the "churn elutriator" devised by Hilgard (12). A stirring device placed at the base of a cylindrical tube dispersed the sample and imparted an upward motion to the water column. In later years, various elutriators appeared ranging from simple one-tube devices to those with a number of tubes varying in size and shape and connected in series. As pointed out by Bayer (3) and others (16), elutriation techniques have several distinct disadvantages: (a) Uniform velocities are very difficult to obtain and maintain over cross section; (b) fine material below about 20μ cannot be fractionated because of difficulties in controlling slow rates of intake flow; and (c) a constant temperature of the system and the inflowing water is required. For these and other reasons, elutriation techniques do not have a widespread use among soil scientists.

Decantation

Separation of the various sized fractions is obtained in the decantation method of analysis by repeated decantation of the dispersed suspension. Early workers in the U. S. Bureau of Soils employed Osborne's "beaker elutriation" technique (17). In this method the sample was dispersed by shaking with ammonia, and an initial separation at 50μ was made by decantation. Material larger than 50μ was ignited, sieved, and weighed. The remaining material was separated into silt, fine silt, and clay by further decantation. Completeness of separation was checked by microscopic examination. Complete analyses of eight to ten samples required about 7 days. Although good results can be obtained by this method, the procedure is too laborious for routine use in most laboratories.

Centrifugation

The centrifuge method (9) as used by the U. S. Bureau of Soils was based on the decantation technique of Osborne. The sand was separated from the silt and clay by beaker decantation, and clay was separated from the silt by repeated centrifuging and decantation. The centrifuge method gave very good results and was less time-consuming than the decantation method. More rapid methods such as the hydrometer and pipette have now generally replaced the centrifuge method for routine mechanical analyses.

Plummet

The plummet method of analysis is based on the change in density that takes place in a suspension at a fixed depth over a period of time. The plummet differs from the hydrometer in that the plummet is suspended from a sensitive weighing device and is lowered into the suspension to a predetermined depth. The mass of the suspended particles is computed from the buoyant effect of the soil suspension. Olmstead, Alexander, and Lakin (19) concluded that although the results showed improvement over those obtained by the hydrometer method, the plummet was not reliable enough to warrant its recommendation even as a field method. Edlefsen and Cole (10) made a comparative study of the plummet and the pipette method. Elipsoidal plummets having volumes of 46, 14, and 4.5 cc. respectively, gave essentially the same results. Good agreement with the pipette was obtained. A spherical plummet gave low results with coarse silt, due to settling of particles on its top. The plummet method apparently has several inherent errors in common with the hydrometer: (a) The suspension is disturbed during immersion and withdrawal. If the plummet is left in suspension, particles settle on the shoulders and low results are obtained. (b) The particles settle out beneath the plummet, leaving an area of decreased density. This, however, is not serious with material having a low settling velocity. (c) An average value of density is obtained, because the plummet extends over a considerable part of the sedimentation column. These sources of error would seem to preclude extreme accuracy, although the method appears to have possibilities for certain types of analysis.

Hydrometer

The hydrometer method, like the plummet, is based on the decrease in density that occurs at a given depth as a dispersed suspension settles. The rate of decrease in density at any given depth is related to the settling velocities of the particles, which in turn are related to their sizes.

Since its introduction by Bouyoucos in 1927 (6), the hydrometer method has been widely used for the particle-size analysis of soils and other materials. A recent procedure for the hydrometer method is described elsewhere (11). The method owes its popularity to the rapidity with which a mechanical analysis may be made and the simplicity of the equipment required. Unquestionably, the method is useful for making certain types of analyses where a considerable

margin of error is permissible. In discussing the merits of the hydrometer, Bouyoucos (7) has said:

From all studies and examinations thus far made, it seems that the hydrometer method is more of a quantitative method and that it is reliable *on all soils that are properly dispersed* and properly stabilized by the reagent. It seems to be especially accurate in the clay fraction (0.005 mm.). In the finer clay fraction (0.002 mm.) it may not be so accurate in some soils that have a very large amount of their finer material just slightly above the 0.002-mm. size. In such soils the hydrometer method indicates a larger content of the 0.002-mm. fraction than the pipette method, but the differences may not be more than 10%.

TABLE 2
Comparison of hydrometer and pipette methods for mechanical analysis of soils

SOIL SERIES	DEPTH	ORGANIC CARBON*	FRACTION	PERCENTAGE OF FRACTION OBTAINED BY	
				Pipette*	Hydrometer†
	<i>inches</i>	<i>per cent</i>			
Estevan	0-2	4.9	Sand	33.3	40.8
			Silt	42.1	46.4
			Clay	24.6	12.8
Estevan	2-13	1.4	Sand	37.9	38.4
			Silt	30.0	30.4
			Clay	32.1	31.2
Maple	0-5	2.7	Sand	45.9	50.4
			Silt	30.1	34.4
			Clay	24.0	15.2
Maple	5-15	0.6	Sand	33.3	34.4
			Silt	29.6	25.8
			Clay	37.1	39.8
Williams	0-6	3.8	Sand	40.5	46.4
			Silt	38.5	41.6
			Clay	21.0	12.0
Williams	15-25	0.6	Sand	41.8	42.8
			Silt	35.2	35.2
			Clay	23.0	22.0

* Analyses by Suzanne Spillman, Bureau of Plant Industry.

† Analyses by Samuel Reiger, Bureau of Reclamation. Samples were not pretreated to remove organic matter and soluble salts.

In a later paper (8) Bouyoucos compared results obtained by the hydrometer and pipette. Of the nineteen samples analyzed by both methods, eight showed differences ranging from 7.5 to 14 per cent in the 2- μ fraction. That complete dispersion of the sample plays a predominating role in reducing the number of erratic results is illustrated in table 2. The hydrometer method fails to give even a fair estimate of the clay content of the surface layers of these soils. In the subsurface layers, where organic matter exerts less influence on the degree of dispersion obtained, results with the hydrometer and the pipette are in close agreement.

In this laboratory about 75 per cent of the time required to make a mechanical analysis is spent in getting the sample ready for the separation of the various fractions. Thus, the rapidity with which an analysis may be performed is limited by the amount of pretreatment necessary for complete dispersion. This pretreatment is considered essential, regardless of the method employed in determining particle-size distribution.

Pipette

The theory on which the pipette method is based is exceedingly simple. All particles having a greater settling velocity than the fraction sought will settle below the point of withdrawal after elapse of a certain time. The time and depth of withdrawal are calculated from Stokes' law. The pipette method was developed independently by Krauss in Germany (15), Robinson in Wales (22) and Jennings, Thomas, and Gardner in the United States (14). Olmstead, Alexander, and Middleton improved the dispersion procedure (18); their method is essentially the one now used in the Soils Divisions of the Bureau of Plant Industry, except that sodium hexametaphosphate is used as the dispersing agent. The pipette method is widely used and is considered to be the most accurate method yet devised for the mechanical analysis of soils.

Procedure for the pipette method as used in the Beltsville laboratories

General statement. Samples are routinely run in sets of eight; the necessary equipment is designed accordingly. The sample is treated with hydrogen peroxide, washed, filtered, and dispersed. The sand is separated from the silt and clay by washing the dispersed sample through a 300-mesh sieve. The various sand fractions are obtained by sieving; 20-, 5-, and 2- μ fractions are obtained by pipetting. The 5- μ fraction is determined in order that current analyses can be readily compared with analyses made prior to January 1, 1938. Organic matter is determined on a separate sample by the dichromate reduction method (20).

Preparation of the sample. The air-dried sample is mixed and quartered. The quarter reserved for analysis is rolled with a wooden rolling pin to break up the clods. The sample is then passed through a sieve with 2-mm. round holes. Rolling and sieving of the coarse material are repeated until only pebbles are retained on the sieve. The material not passing the sieve is weighed and reported as a percentage of the air-dry weight of the whole sample.

Removal of organic matter. A 10-gm. sample of the air-dry soil containing no particles larger than 2 mm. is weighed on a rough balance and placed in a 250-ml. electrolytic pyrex beaker. About 50 ml. of water is added followed by a few milliliters of 30 per cent hydrogen peroxide. The beaker is then covered with a watch glass. If a violent reaction occurs, the cold hydrogen peroxide treatment is repeated periodically until no more frothing occurs. The beaker is then heated to about 90°C. on an electric hot plate. Hydrogen peroxide is added in 5-ml. quantities at about 45-minute intervals until the organic matter is essentially removed as determined by visual inspection. Heating is then continued for about 30 minutes to remove any excess hydrogen peroxide.

Removal of dissolved mineral matter. Following the hydrogen peroxide treatment, the beaker is placed in a rack and about 150 ml. of water is added by means of a jet strong enough to stir the sample well. The suspension is filtered by means of a short Pasteur-Chamberlain filter of "F" fineness. Five such washings and filterings are usually sufficient except for soils containing much coarse gypsum. Soil adhering to the filter is removed by applying a gentle back-pressure and using the forefinger as a policeman. The beaker is then dried on a steam bath, placed overnight in an oven at 110°C., cooled in a desiccator,

and then weighed to the nearest milligram. After the sample is transferred to a nursing bottle for dispersion, the oven-dry weight of the beaker is obtained. The weight of the oven-dry organic-free sample is used as the base weight for calculating the percentages of the various fractions.

Dispersion of the sample. To the oven-dry sample, is added 10 ml.¹ of sodium hexameta-phosphate dispersing agent², and the sample is transferred to an 8-ounce pyrex glass nursing bottle by means of a funnel, a rubber policeman, and a jet of water. The volume is made to 6 ounces, and the bottle is stoppered and shaken overnight on a horizontal reciprocating shaker with 120 oscillations per minute.

Separation of the sands from silt and clay. The dispersed sample is washed on a 300-mesh sieve, the silt and clay passing through the sieve into a liter graduated cylinder. The sieve is held above the cylinder by means of a clamp and a stand. Jets of water should be avoided in washing the sample. The sieve clamp is tapped gently with the side of the hand to facilitate the washing procedure. Washing is continued until the volume in the cylinder totals about 800 ml. The sands and some coarse silt remain on the sieve. It is necessary that all particles of less than $20\ \mu$ diameter be washed through the sieve. The sieve is removed from the holder, placed in an aluminum pan, and dried at $110\text{--}120^{\circ}\text{C}$. While the sands are drying, another sieve is used for the next sample. The material on the sieve is then brushed into a platinum dish and further dried for about 2 hours. The dish is then placed in a desiccator, the contents to be sieved and weighed when convenient. The silt and clay suspension in the cylinder is made up to 1 liter with distilled water, covered with a watch glass, and set aside until the pipettings are to be made.

Pipetting. Pipettings are made for the 20-, 5-, and $2\text{-}\mu$ particles in the order named. The 20- and $5\text{-}\mu$ particles are pipetted at a 10-cm. depth, the sedimentation time varying according to the temperature. The $2\text{-}\mu$ fraction is pipetted after a predetermined settling time (usually 6 to $6\frac{1}{2}$ hours), the depth varying according to the time and temperature. A Lowy 25-ml. automatic pipette with a filling time of about 12 seconds is used. Prior to each pipetting, the material in the sedimentation cylinder is stirred for 6 minutes with a motor-driven stirrer (8 minutes if the suspension has stood for more than 16 hours). After removal³ from the stirrer a length of pipe insulating cover is slipped over the sedimentation cylinder and the suspension is stirred for 30 to 60 seconds with a hand stirrer³, an up and down motion being used. The time is noted at completion of the stirring. About 1 minute before the sedimentation is complete, the tip of the 25-ml. pipette is lowered slowly into the suspension to the proper depth by means of a Shaw pipette rack (23). The pipette is then filled and emptied into a 60-ml. weighing bottle having an outside cover. One rinse from the pipette is added. A vacuum is used to dry the pipette for use on the next sample. The weighing bottle is dried in an oven at 95 to 98°C . and then further dried for about 4 hours at 110°C .

¹ A similar volume of dispersing agent is placed in a liter cylinder, the volume made to 1,000 ml. and well mixed. A sample is taken with the pipette, dried, and weighed to obtain the weight correction referred to in the section on calculations. This weight correction is obtained for each new solution of sodium metaphosphate.

² The preparation and use of sodium metaphosphate as a dispersing agent for soils is described by Tyner (25). The dispersing solution is similarly prepared in this laboratory: 125 gm. of monosodium phosphate ($\text{NaH}_2\text{PO}_4 \cdot \text{H}_2\text{O}$) is slowly heated in a platinum dish to 650°C . This temperature is held for $1\frac{1}{2}$ hours. The platinum dish and its contents are removed from the furnace and the sodium metaphosphate is cooled rapidly by pouring it out in narrow strips on a clean marble slab. The dispersing agent is made by dissolving 35.70 gm. sodium metaphosphate and 7.94 gm. sodium carbonate in 1 liter volume. The sodium carbonate is used as an alkaline buffer to prevent the hydrolysis of the metaphosphate back to the orthophosphate which occurs in acidic solutions.

³ This stirrer is made by fastening a circular piece of perforated brass sheeting to one end of a brass rod. A wide rubber band is placed around the edge of the brass sheeting to prevent abrasion.

The initial drying is done at a lower temperature to prevent spattering of the suspension. The weighing bottle is then cooled in a desiccator containing phosphorus pentoxide as a desiccant and weighed.

Sieving and weighing the sand fractions. The dry sands, including some coarse silt, are weighed and brushed into a nest of sieves⁴. (An 80-mesh sieve is included in order to obtain I.S.S.S. fraction I). They are then shaken for 3 minutes on a shaker having vertical and lateral movements of one-half inch making 500 oscillations per minute. For a different shaker the time of shaking would have to be determined by microscopic study. The summation method of weighing is used. The first sand fraction is weighed, the second fraction added to it, the total weight determined and so on. If the sum of the weights of the fractions is equal to the total weight it is assumed that no weighing error has been made.

Calculations of results.

Pipetted fractions:

$(A - B) KD$ = per cent of pipetted fraction

where A = weight in grams of pipetted fraction, B = weight correction for dispersing agent (in grams), $K = \frac{1,000}{\text{volume contained by pipette}}$, $D = \frac{100}{\text{organic-free oven-dry weight of total sample}}$.

The 20- μ fraction - the 2- μ fraction = I.S.S.S. fraction III.

U.S.D.A. silt is obtained by subtracting the sum of the percentages of sand and clay from 100.

I.S.S.S. fraction II is obtained by subtracting the sum of the percentages of fractions I, III, and IV from 100.

Sand fractions:

Weight in grams of fraction on sieve $\times \frac{100}{\text{organic-free oven-dry weight of total sample}}$ = per cent of fraction.

REFERENCES

- (1) ALEXANDER, L. T. 1930 The dispersion and mechanical analysis of certain soils high in sesquioxides. *Internatl. Soc. Soil Sci. Proc., Res. Sup.* 2: 72-76.
- (2) BAVER, L. D. 1930 The effect of organic matter upon several physical properties of soils. *Jour. Amer. Soc. Agron.* 22: 703-708.
- (3) BAVER, L. D. 1940 *Soil Physics*. New York and London.
- (4) BEALE, O. W. 1939 Dispersion of lateritic soils and the effect of organic matter on mechanical analysis. *Soil Sci.* 48: 475-481.
- (5) BODMAN, G. B. 1928 The hydrogen peroxide-hydrochloric acid treatment of soils as a method of dispersion in mechanical analysis. *Soil Sci.* 26: 459-470.

⁴ Sieves and specifications are as follows:

Sieve Opening mm.	Specifications
1.0	Perforated brass plate, round holes, number 3 straight, 0.04-inch diameter holes, 240 holes per square inch.
0.5	Perforated brass plate, round holes, number 00 staggered, 0.02-inch diameter holes, 714 holes per square inch.
0.25	60-mesh, Bureau of Standards (Phosphor Bronze wire cloth)
0.177	80-mesh, Bureau of Standards (Phosphor Bronze wire cloth)
0.105	140-mesh, Bureau of Standards (Phosphor Bronze wire cloth)
0.047	300-mesh, Phosphor Bronze wire cloth, 0.0015 wire.

- (6) BOUYOUCOS, G. J. 1927 The hydrometer as a new method for the mechanical analysis of soils. *Soil Sci.* 23: 343-353.
- (7) BOUYOUCOS, G. J. 1930 A comparison of the hydrometer method and pipette method for making mechanical analysis of soils, with new directions. *Jour. Amer. Soc. Agron.* 22: 747-751.
- (8) BOUYOUCOS, G. J. 1934 A comparison between the pipette method and the hydrometer method for making mechanical analysis of soil. *Soil Sci.* 38: 335-345.
- (9) BRIGGS, L. J., MARTIN, F. O., AND PEARCE, J. R. 1904 The centrifugal method of mechanical soil analysis. U.S. Dept. Agr., Bur. Soils Bul. 24.
- (10) EDLEFSEN, N. E., AND COLE, R. C. 1936 A comparison of the specific gravity balance and the pipette methods of determining density of soil suspensions. *Soil Sci.* 42: 131-137.
- (11) Highway Materials 1942 *Standard Specifications for Highway Materials and Methods of Sampling and Testing*, Part II: 156-165. Amer. Assoc. State Highway Off., Washington, D. C.
- (12) HILGARD, E. W. 1906 *Soils; Their Formation, Properties, Composition, and Relations to Climate and Plant Growth in the Humid and Arid Regions*. New York and London.
- (13) HOPKINS, C. G. 1899 A plea for a scientific basis for the division of soil particles in mechanical analysis. *U. S. Dept. Agr. Div. Chem. Bul.* 56: 64-66.
- (14) JENNINGS, D. S., THOMAS, M. D., AND GARDNER, M. 1922 A new method of mechanical analysis of soils. *Soil Sci.* 14: 485-499.
- (15) KRAUSS, G. 1923 Über eine neue Methode der mechanischen Bodenanalyse, usw. *Internatl. Mitt. Bodenk.* 13: 147-160.
- (16) Methods of analyzing sediment samples 1941 Report 4. St. Paul U. S. Engin. Dist. Sub-Office, Hydraulic Lab., Univ. Iowa, Iowa City, Iowa.
- (17) Methods of the mechanical analysis of soils and of the determination of the amount of moisture in soils in the field 1896 U. S. Dept. Agr. Div. Soils Bul. 4.
- (18) OLMSTEAD, L. B., ALEXANDER, L. T., AND MIDDLETON, H. E. 1930 A pipette method of mechanical analysis of soils based on improved dispersion procedure. U. S. Dept. Agr. Tech. Bul. 170.
- (19) OLMSTEAD, L. B., ALEXANDER, L. T., AND LAKIN, H. W. 1931 The determination of clay and colloid in soils by means of a specific gravity balance. *Amer. Soil Survey Assoc. Bul.* 12: 161-166.
- (20) PEECH, M., et al. 1947 Methods of soil analysis for soil fertility investigations. U. S. Dept. Agr. Cir. 757.
- (21) ROBINSON, G. W. 1922 Note on the mechanical analysis of humus soils. *Jour. Agr. Sci.* 12: 287-291.
- (22) ROBINSON, G. W. 1922 A new method for the mechanical analysis of soils and other dispersions. *Jour. Agr. Sci.* 12: 306-321.
- (23) SHAW, T. M. 1932 New aliquot and filter devices for analytical laboratories. *Indus. and Engin. Chem., Analyt. Ed.* 4: 409.
- (24) TRUOG, E., et al. 1937 Procedure for special type of mechanical and mineralogical soil analysis. *Soil Sci. Soc. Amer. Proc.* (1936) 1: 101-112.
- (25) TYNER, E. H. 1940 The use of sodium metaphosphate for dispersion of soils for mechanical analysis. *Soil Sci. Soc. Amer. Proc.* (1939) 4: 106-113.
- (26) WINTERS, E. JR., AND HARLAND, M. B. 1930 Preparation of soil samples for pipette analysis. *Jour. Amer. Soc. Agron.* 22: 771-780.

METHODS OF MEASURING SOIL STRUCTURE AND AERATION

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Growing appreciation of the significance of the influence of physical conditions of soil on plant growth and soil behavior has resulted in many investigations of these conditions and the factors affecting them. For such studies, methods of characterizing the particular condition quantitatively and objectively have been devised. In determining well-defined and easily recognized physical properties, such as particle density, only a few methods, usually differing merely in minor respects, have been developed. For such a broadly defined property as soil structure, however, many evaluating procedures have been developed. These differ not only in procedural details, but in the identity of the particular characteristic that is measured.

Soil structure is commonly defined as the arrangement of the naturally occurring soil particles. Complete specification of such a condition, even as an instantaneous value, is essentially impossible, and the task becomes even more involved if the variations in structure with time are to be described. Its evaluation, therefore, is made in terms of one or more of such related properties as porosity, aggregate size-distribution, or permeability. As a result, many persons have come to consider aggregation, bulk density, or some other measurable characteristic as synonymous with soil structure; hence soil structure has come to mean different things to different persons.

Since no single procedure is available for evaluating soil structure in its broadest sense, this article discusses several related properties commonly used as measures of soil structure. No attempt is made to include all such properties or to give detailed procedures or descriptions of the equipment used; such details will be found in the appropriate reference in the bibliography. The selection of the particular procedures used herein should not be interpreted as any reflection on those not included. The choice has been made largely on the basis of the author's experience with the methods and is therefore limited to such procedures as have been used in his laboratory. Modification of certain details of many of procedures may be advisable to meet the requirements of a particular problem.

STRUCTURE MEASUREMENTS BASED ON SOIL POROSITY

One of the most obvious physical characteristics of soil is its granular porous nature. The voids that exist between individual soil particles represent channels for movement and retention of the liquid and gaseous components of the soil and constitute the part of the total soil volume that is available for root development. Several methods of evaluating soil structure based on the description of the soil pores have been developed and are discussed below.

Measurement of total porosity

The simplest characterization of the soil pore system is the determination of the proportion of the macroscopic soil volume that is not occupied by solids. Two types of methods are used for this purpose.

Apparent density. Because of the volume occupied by voids, the apparent density (also known as *volume weight* and *bulk density*) is considerably less than that of the solid soil constituents. Thus, it is possible to calculate the percentage of the total soil volume that is occupied by the voids (P) from data on the apparent density (Da) and the true density (Dr) of the solid constituents by use of the relation $P = \frac{(Dr - Da)}{Dr} \times 100$. Since the value

of Dr is essentially constant for mineral soil (2.60–2.65 gm./cc.), the determination of apparent density is commonly used directly as a criterion of soil structure.

Several methods have been developed for measuring the apparent density of soil. It is necessary to determine both the volume and the mass of a given sample without changing their ratio from that in the undisturbed soil. Since it is assumed that all the voids are filled with air, it is also necessary to determine the moisture content of the sample and correct the mass to a water-free basis.

To determine the apparent density of discrete soil masses such as clods or large aggregates, the macroscopic volume is determined by measuring the loss in weight that results when the soil mass is immersed in a liquid of known density (34). The clod is weighed in air, then coated with a water-impermeable material such as paraffin, reweighed in air (to determine the amount of paraffin added), and finally weighed while immersed in water. The clod is removed from the water, broken open, and sampled for moisture content. The apparent density is calculated from the oven-dry weight of the clod and its volume, the latter being determined from the loss in weight upon immersion. This volume figure is corrected for the volume of the paraffin coating.

Another technique that may be used to determine the apparent density is to dig a small hole, weigh the soil that is removed, correct this weight to an oven-dry basis, and divide this value by the volume of the hole (10). The volume of the irregular-shaped hole can be determined by measuring the volume of dry sand required to fill it. A viscous fluid, such as heavy motor oil, which will not penetrate into the soil, also can be used to determine the volume at sites where residues of such materials are not objectionable.

Perhaps the most satisfactory method of measuring apparent density is by means of "core samplers" (6, 25, 43). Although these instruments may vary greatly in size and form, they are commonly circular in cross section with a diameter of about 2 to 3 inches. The length of the sample also is variable, but usually is 1 to 4 inches. Core samplers consist of a steel cylinder, inside which a cylindrical sample holder of brass, waxed cardboard, or tin is fitted against a shoulder in the steel cylinder. One end of the steel cylinder, which projects beyond the sample cylinder is sharpened and constitutes the cutting edge of the sampler. All the sharpening is done on the outer surface of the steel tube so that the cutter head and the sample ring have a uniform cylindrical bore. If the sampler is to be used only for apparent density measurements, it is desirable to increase slightly the inside diameter immediately behind the cutting edge and then carry this increased diameter uniformly through the remainder of the cutting head and the sample holder. This greatly reduces the friction between the soil and the sampler and prevents compression of the sample while the core is being taken.

After the sampler has been forced into the soil and carefully removed, the sample holder and its contents are removed. The ends of the soil cylinder are cut off flush with the ends of the sample holder, giving a core of soil of known volume. The core is then weighed and sampled for moisture. The ratio of the oven-dry weight to the volume of the core is recorded as the apparent density.

Care must be taken during sampling to avoid compression of the sample. This is particularly true in very loose soils and those having high moisture contents. In soils containing coarse gravel, stones, or undecomposed plant residues, satisfactory cores are often difficult to obtain. Under such conditions careful examination of each core is necessary. Faulty cores can usually be detected and should be discarded.

Direct determination of pore volume. The volume of air-filled voids in a sample of soil

can be determined directly by making use of the relation that exists between pressure and volume of a confined gas (42). This relationship is expressed in the familiar Boyle's law, which states that at constant temperature the product of the pressure and volume of a confined body of gas is a constant.

To determine the volume of the air-filled voids in a soil by this method, a sample of known macroscopic volume is placed in a closed vessel and subjected to a change of gas volume. From the resulting pressure change of the confined gas and from data on the physical dimensions of the system the required volume can be calculated. Devices for making measurements of this type have been developed (23, 27) that permit rapid determination of void volume in the field. Since the voids filled with water do not contribute to the void volume as measured by this technique, it is possible to study the volume of air-filled pores over a range of soil moisture conditions without actually determining the amount of water in the sample. This increases the usefulness of this technique as a field method of measurement.

Measurement of pore-size distribution

Although determination of the total volume of voids in a soil is a useful criterion for characterizing structural conditions, interpretation of such data in terms of the behavior of the soil is further clarified when information as to the size distribution of the voids also is available (5, 35). This additional information may consist of the percentage distribution of voids in two or more discrete size classes or of a continuous size-distribution curve. In either case the data are obtained by subjecting an initially saturated sample of soil to suction on a suitably designed porous surface and determining the volume of water withdrawn as a function of the suction applied. The water that remains in the soil at equilibrium with a given applied suction is assumed to be held only in those voids in which the total curvature is greater than that required to withstand the applied suction. If the voids are assumed to be circular in cross-section, this relation between interfacial curvature and pressure reduces to the familiar height-of-capillary-rise equation: $h = \frac{2T}{rdg}$, in which the height of rise h (which is proportional to the interfacial pressure difference) is shown to vary directly with the surface tension T and inversely with the radius of the capillary. From this equation the size of the largest pore that would remain filled at any given applied suction can be calculated.

One serious limitation to this interpretation of pore-size vs. suction data is that the height-of-capillary-rise equation applies only to those pores in which an air-water interface exists. Since the soil voids constitute a three-dimensional network of cell-like cavities interconnected through narrow necks, the water in a given large pore will not be drained until the applied suction exceeds the value required to cause an air-water interface to penetrate through the largest of the necks connecting the large pore with the atmosphere. As pore-size studies invariably start with a fully saturated soil, this so-called "blocked-pore effect" results in a serious shifting of the pore-size distribution curve towards the small-pore range of sizes. The blocked-pore effect also distorts the results based on two or more discrete-size classes of pores by underestimating the volume percentage of the larger-size class or classes.

Determination of discrete size classes. For this purpose two ranges of pore sizes are commonly recognized (20, 24). These are called *capillary and noncapillary pores, macropores and micropores*, or simply *large and small pores*. The separation is usually made on the basis of the water retained by the sample at a suction of approximately 50 cm. of water. A sample of soil having natural structure is treated as described above and allowed to reach a moisture equilibrium with water under 50 cm. of water tension. The sample is removed from the porous plate, weighed, oven-dried, and reweighed. From these data, the weight of the saturated sample, the macroscopic volume of the sample, and the density of the solid soil constituents, it is possible to calculate the total porosity, the volume of pores drained at a tension of 50 cm. of water, and the volume undrained at this tension.

If more than two size classes of pores are to be determined, moisture equilibria are established at additional tensions and the volume of pores undrained is determined. In view of the blocked-pore effect, it is preferable to report such results as percentage of total pore volume remaining filled at a tension of so many centimeters of water rather than as percentage pore volume having radii less than a certain value as calculated from the height of capillary-rise equation.

Continuous pore-size distribution curve. By increasing the number of pore-size classes it is possible to increase progressively the exactitude of the characterization of soil porosity. A continuous pore-size distribution curve is approached when the number of classes becomes very large. To obtain such a curve, a sample of soil is saturated, then subjected to increasing tensions. The relation between moisture content, θ and the tension T is plotted with θ as the dependent variable, and the slope of the curve, $\frac{d\theta}{dT}$, is measured at a number of values

of T . A new curve is then drawn with $\frac{d\theta}{dT}$ as a function of T . This curve gives a picture of the size distribution of the soil voids, subject to uncertainties that arise from the blocked-pore effect. Bimodal pore-size distribution curves are commonly found in well-aggregated soils as a consequence of the intra- and interaggregate pores. The stability of the pore-size distribution may be evaluated by determining the ratio of the heights of peaks of the $\frac{d\theta}{dT}$ vs. T curve before and after the sample is subjected to a weathering cycle of repeated wetting and drying. Feng and Browning (12), however, report that the quantity $\frac{d\theta}{dT}/T$ at the peak value of $\frac{d\theta}{dT}$ is a better measure of structure stability.

Microscopic techniques for evaluating soil porosity

In the use of the microscope for evaluating soil porosity, two types of observations are made (11, 22).

For qualitative studies of the size and configuration of the larger voids, the soil is observed directly with a low power microscope and incident light. Such observations are useful in establishing the relationship of the size, shape, and configuration of the voids between the larger soil particles and aggregates but is limited to those structural features that are exposed on the surface of the sample. Observations of this type can be conducted in the field and are especially useful in studies of soil morphology. The nature of root development with respect to soil structural characteristics can also be studied in this way.

For a more detailed quantitative description of soil porosity, the thin-section technique is used (17, 22). For this purpose the soil sample is impregnated with a material that subsequently hardens. A flat surface is ground on the hardened sample, which is then cemented to a glass slide. The soil chip is then carefully ground until only a thin layer remains on the slide. This specimen is examined under the microscope with transmitted light. The size distribution of the voids is determined by measuring the diameters of the

voids that are intercepted by a line traversing the sample (18). By making such measurements on a sufficiently large number of traverses, a statistical measure of pore-size distribution is obtained. Such measurements can be greatly facilitated by projecting the enlarged image of the specimen on a horizontal plane surface of coordinate paper (29).

STRUCTURE MEASUREMENTS BASED ON SOIL AGGREGATES

Under natural conditions in most soils a high proportion of particles fail to function as individuals but are associated into secondary units called *aggregates*. The physical behavior of a soil is strongly affected by the number, size, arrangement, and stability of these secondary particles. Since aggregates vary greatly in size and shape and in their ability to resist dispersion, these are the characteristics that have been used to describe them. Of the numerous techniques that have been developed for evaluating aggregate size and stability, a few of the more widely used are discussed below.

Measurement of aggregate-size distribution

Screens can be used for separating the several size classes of most soil aggregates. Size fractionation may be extended to finer sizes by use of either a pipette or hydrometer technique comparable to those used in mechanical analysis, although considerable uncertainties may arise from the indefinite density of the aggregates.

Aggregate-size determination by wet-sieving. This is the technique most widely used for aggregate analysis at present. The procedures are essentially comparable to that described by Yoder (44). For this determination a set of six 6-inch screens having openings of 5.0, 2.0, 1.0, 0.5, 0.25 and 0.10 mm., respectively, is used. These screens are fitted one above the other with the joints between them sealed with rubber bands. The 0.10-mm. screen is placed on the bottom of the set and the others are assembled above it in order of increasing size of opening. The whole assembly is attached to a crankshaft that raises and lowers the screens through a distance of 1½ inches at the rate of 30 strokes per minute. The screens are immersed in water to such a depth that the water surface is at the level of the top screen when the set of screen is at its highest point in its oscillatory motion.

With the screens in their highest position, a 50-gm. sample of soil is evenly distributed over the surface of the upper screen. The machine is started and the screens are raised and lowered in the water for 30 minutes. The machine is then stopped and the screens are removed from the water and allowed to drain. The rubber bands are removed. The soil retained on each screen is transferred to an evaporating dish with the aid of a wash bottle. The excess water is poured off and the sample is oven-dried, weighed, and reported as the uncorrected weight of water-stable aggregates larger than the opening of the screen from which the sample was obtained but smaller than the opening of the screen above. When the six screens are used, seven size classes of aggregates are determined: >5.0, 5.0-2.0, 2.0-1.0, 1.0-0.5, 0.5-0.25, 0.25-0.10, and <0.10 mm.

In soils containing significant amounts of primary particles > 0.10 mm. in diameter, the weight of material retained on each screen must be corrected for the weight of primary particles in that particular size class. This is done after the oven-dried soil from each screen has been weighed. This material is thoroughly dispersed in an excess of water with the aid of a rubber policeman, and the suspension is poured over the screen from which the particular sample was taken. The material retained on the screen is transferred to an evaporating dish, oven-dried, weighed, and subtracted from the original uncorrected weight of aggregates of that size class.

Aggregate-size distribution by dry-sieving. In certain instances where the ability of the aggregates to resist breakdown in water is not considered important, the size distribution of aggregates can be determined by dry-sieving. For this determination the soil sample is placed on the upper (coarsest) of a nest of screens, which are then gently shaken a definite number of times. The material retained on each screen is collected and weighed as in the wet-sieving procedure. The range of screen sizes used for dry-sieving is usually greater than that used in wet-sieving. For example, Cole (8), in a study on the effect of tillage on soil macrostructure, used screens having openings of the following sizes: $4\frac{1}{2}$, $3\frac{1}{2}$, $1\frac{1}{2}$, $\frac{1}{2}$, $\frac{1}{4}$, $\frac{1}{8}$, and $\frac{1}{16}$ inches.

Chepil and Bisal (4) devised a rotary apparatus for dry-sieving soil aggregates. This device consisted of coaxial perforated cylinders of different diameters mounted on a 4° incline. The perforations were largest on the inner cylinder and decreased progressively in succeeding cylinders. The perforations used were 38, 12.7, 6.4, 2.0, 0.83, and 0.42 mm. The soil sample was introduced into the inner cylinder at its upper end, and as the cylinders rotated (14 revolutions per minutes) the soil aggregates were separated into the several size classes and discharged from the lower ends of the several cylinders.

Other methods of determining aggregate-size distribution. In addition to the techniques involving the use of sieves, several other methods have been devised. In general, these techniques have not been widely used and are given only brief attention in this discussion.

Sedimentation methods already mentioned briefly as applying to the subsieve range of aggregate sizes have been used for complete aggregate analysis. Both the pipette (21) and the hydrometer (14) methods of measuring suspension density have been used. Cole and Edlefsen (7) devised a sedimentation tube for aggregate-size classification in which the weight of soil on each of several cylindrical sleeves in the tube was determined. Aggregate sizes were segregated by allowing the sample to settle for a given time while the tube was in a vertical position and then to collect on the liner sleeves following the rotation of the tube into a horizontal position.

A direct microscopic measurement of aggregate sizes has been developed and used in studying soil structure (29). In this procedure the sample is uniformly distributed in a viscous fluid in a flat-bottomed glass dish and allowed to settle out on the bottom of the vessel. This dish is placed under the microscope, and the image of the aggregates is projected on a suitable viewing screen. The size distribution of the aggregates is then determined by a counting technique comparable with that described under pore-size measurements (31). The microscopic technique permits the use of only a small sample and gives information regarding the shape and morphological features of the aggregates that are not obtained by the methods previously described.

Measurements of aggregate stability

The degree to which they resist dispersion is the second characteristic used to evaluate soil aggregates. For significance in affecting the physical behavior of field soils, aggregates must have sufficient stability to maintain their identity when subjected to such dispersive actions as raindrop impact, tillage operations, percolating water, and the compressive force of the overlying soil mass.

Studies of aggregate stability are usually made by measuring the decrease in aggregation following successive manipulations that favor aggregate disintegration. These measurements may be made on the entire soil, in which case the effects on the aggregate-size distribution curve is measured, or they may be made on a particular size class of aggregates.

Methods using preliminary shaking. The soil sample is placed in a closed container with an excess of water and subjected to agitation in a reciprocating or end-over-end shaker for a known length of time (1, 2, 15). The soil is then transferred to a nest of screens and the

aggregate size is determined by the wet-sieving procedure. By comparison of the results obtained following different degrees of preliminary shaking, the relative stability of the soil aggregates is obtained. Studies of this kind commonly reveal significant differences in aggregate stability between samples having similar size distributions as determined by the wet-sieving method.

The falling-drop technique. A procedure for measuring the energy required to cause aggregate disintegration has been developed by McCalla (26). For this determination, individual 0.15-gm. aggregates are used. The aggregate is placed on a 1.0-mm. screen directly beneath the tip of a burette mounted 30 cm. above the sample. By careful adjustment of the burette, water is allowed to fall dropwise and strike the aggregate. The number of drops required to destroy the aggregate to the extent that it drops through the supporting screen is recorded. From this figure, the height of fall, and the drop size, the energy expended in causing disintegration is calculated.

Single-screen wet-sieving technique. The water-stability of aggregates of a particular size class can be determined by the single-screen technique (2, 36). Aggregates of a particular size class are separated from the soil by dry-sieving. A small sample of these is placed on the screen of a mechanical agitator, which is then set in motion for a known time. The weight of aggregates retained on the screen at the end of this time is determined. Another sample is then placed on the screen and subjected to agitation for a longer period. After several such determinations the percentage of original aggregates remaining on the screen as a function of the agitation time is plotted. The slope of the best fitting straight line through the data points is taken as an index of aggregate stability.

MISCELLANEOUS METHODS OF MEASURING SOIL STRUCTURE

Although measurements of soil aggregation and porosity characteristics are the most commonly used techniques for evaluating soil structure, several other types of measurements have been proposed and used to a limited extent. In general, these techniques are particularly suited for certain specific soils or soil conditions.

Penetrometer methods

Soils differ widely in their resistance to penetration. Such differences are related to the cultural practices that have been used and to the moisture content as well as to the mechanical composition of the soil. Penetrometer methods are particularly useful in studying the effect of tillage operations on physical properties of the soil and in investigations involving soil crusts, plowpans, or other compaction phenomena. Two general types of penetrometers are in use for studies of this nature.

Impact penetrometers. These are the simplest type of penetrometers (13, 41). The data obtained consist of measurements of the depth of penetration of a suitably shaped probe following one or more impacts. In one such device, the probe itself is allowed to fall from a given height through a vertical guide tube, and the depth of penetration of the gently tapered conical tip is measured. In another penetrometer, the probe is set on the surface of the soil and then driven in by a series of impacts from a falling weight. The depth of penetration following each impact is measured and plotted as a function of the number of impacts. The slope of the curve is used as an index of "penetrability" on the soil.

Steady-load penetrometers. In these instruments the probe is forced into the soil by application of a steadily increasing force (9, 32, 39). This force is usually transmitted to the probe through a compression spring. Changes in length of this spring are used as a measure of the force being applied to the probe. The Proctor needle (30), a device of this type, is

widely used to evaluate compaction. Self-recording features have been incorporated in some of the penetrometers of this type and yield depth vs. force curves which are useful in studying the effect of tillage and other cultural practices on soil structural conditions.

Measurement of soil structure with dynamometers

Structural conditions affect the draft of tillage implements used on a soil. The effect can be evaluated by dynamometers which will record the force required to move the implement through the soil. Suitable devices of this type have been developed (16) and have proved useful in characterizing the physical condition of field plots that have received different cultural treatments.

Compressibility curves as indexes of soil structure

Scott Blair (37, 38) used a compression device for evaluating structural conditions in the field. A flat circular plate was placed on the soil surface and then loaded by lowering weights on it from above. The resulting deformation of the soil beneath the loaded plate was plotted as a function of the square root of the load. Several characteristics of the resulting compression curve were evaluated and interpreted in terms of physical properties of the soil.

METHODS OF MEASURING SOIL AERATION

Structural conditions strongly affect soil aeration, which is also conditioned by such environmental factors as temperature, biological activity, and moisture conditions. For this reason, predictions of degree of aeration from soil structure measurements alone are not reliable. Several methods have been developed for direct evaluation of the aeration status, but, as in the case of soil structure measurements, there is no single characteristic that can be used to describe such a complex phenomenon as soil aeration.

Measurement of the composition of the soil atmosphere

One of the most obvious means of characterizing the soil atmosphere is to determine its composition (33). A sample of soil air is obtained from a given location by inserting into the soil a small-bore metal tube through which the sample is drawn with a suitable pump. A rubber aspirator bulb or a hand-operated mercury displacement pump is usually used for this purpose. It is desirable to keep the volume of the sampler, pump, and necessary connecting tubing as small as possible to minimize the dilution effect of the gas originally contained therein on the sample drawn from the soil. This dilution effect is essentially eliminated if the system is flushed with two or more charges of soil air, which are then discarded. If convenient, the sample of gas should pass directly from the sampler into the gas analyzer. If this is not feasible, the samples can be collected in glass bottles under mercury or acidulated water and held until the analyses can be made.

Care must be exercised in sampling the soil atmosphere at shallow depth to prevent contamination with air from above the soil surface that may be drawn through channels along the side of the sampler or through natural channels such as cracks, wormholes, and root channels. If the composition of the soil atmosphere at a given point is to be followed for a time, it is convenient to install a suitable "sampling-well" at that point to avoid the disturbances caused by repeated insertion and removal of the sampling tube (3). Such wells can be easily made by attaching a short length of large-bore tubing to the lower end of a length of $\frac{1}{4}$ inch copper tubing. The larger tubing is lightly packed with glass wool and installed at the desired depth in the soil. The free end of the $\frac{1}{4}$ inch tube is suitably sealed and left exposed above the soil surface. Samples of soil air are then obtained by unsealing this tubing and attaching the usual type of pumping device.

The volume percentage of oxygen and carbon dioxide in the sample of soil air can be determined with any of the standard gas analysis devices available commercially. In these, the change in volume following the absorption of each of the gases is determined. If only the oxygen concentration is desired, the analysis can be quickly and conveniently made with a Pauling oxygen analyser (28). Since the magnetic susceptibility of oxygen is much greater than that of the other gases normally encountered, this device indicates the oxygen content based on a measurement of that property of the gas sample.

Oxygen-supplying power

Experience has shown that measurements of the composition of the soil atmosphere do not adequately characterize soil aeration. Some measure of the ability of a soil to supply oxygen to a given absorbing surface is also needed. This can be obtained by measuring the rate of diffusion of oxygen into an oxygen-free chamber buried in the soil (19). Care must be exercised to prevent entry of oxygen from above the soil surface through channels along the side of the measuring device or through other artificial channels. Since it is desired to measure oxygen diffusion, the total pressure in the measuring chamber must be kept equal to atmospheric pressure throughout the determination.

If a series of measurements are to be made at a given point in the soil, a diffusion chamber that can be left in position should be used. For single determinations, the device can conveniently be in the form of a probe that is inserted in the soil to the desired depth and removed after the measurement is made.

After the diffusion chamber is installed in the soil it is closed and flushed with oxygen-free nitrogen. When the system has returned to atmospheric pressure, the chamber is opened to the soil atmosphere, and gases are allowed to diffuse into and out of the chamber for a known time. The chamber is again closed, and the oxygen content of the contained gas is determined. The change in oxygen content during the diffusion period is used as a measure of the oxygen-supplying power.

Oxidation-reduction measurements

When anerobic conditions develop in soil, many constituents are reduced. The relative proportion of oxidized and reduced ions can be determined by measuring the oxidation-reduction or redox potential of the system containing the ions. Usually these measurements are made on samples suspended in water or 0.1 N H_2SO_4 . Care must be taken to prevent either oxidation or reduction during the sampling and storage period. A soil probe devised by Starkey and Wight (40) permits measurement of pH and redox potential of saturated soils *in situ*.

Potentiometric titrations of soil extracts with an oxidizing agent such as KMnO_4 also is used to characterize aeration conditions. Since such titrations give a measure of the quantity of reduced materials present, they supplement the potential measurements, which indicate the relative amounts of oxidized and reduced ions.

For a thorough discussion of the use of oxidation-reduction measurements in characterizing soil aeration, the reader is referred to a report by Starkey and Wight (40).

CONCLUSIONS

The complete physical description of the structural condition of soil is essentially impossible. Procedures have been developed, therefore, for evaluating certain measurable characteristics that serve as indicators of soil structure. In general, these procedures involve a number of manipulations that are selected on purely arbitrary bases. For this reason, many measurement techniques have been developed which differ only slightly in certain procedural details. Under some circumstances one method may seem to be of greater usefulness than

another, whereas the reverse may be true under other conditions. Hence, it is not possible to select any one measurement or procedure as *the* way of measuring soil structure.

It is the opinion of the author that the most promising approach to the evaluation of soil structure, particularly as this affects plant growth, lies, not in the elaboration of the physical architecture of the soil, but in the description of the air, water, temperature, and compaction conditions that greatly influence root activity and plant growth. If such measurements are to be significant, much additional quantitative information is needed on the relation of these factors to plant growth.

REFERENCES

- (1) ALDEFER, R. B., AND MERKLE, F. G. 1941 The measurement of structural stability and permeability and the influence of soil treatments upon these properties. *Soil Sci.* 51: 201-202.
- (2) BOUYOUCOS, G. J. 1929 The ultimate natural structure of soils. *Soil Sci.* 28: 27-37.
- (3) BOYNTON, D., AND REUTHER, W. 1939 A way of sampling soil gases in dense subsoil and some of its advantages and limitations. *Soil Sci. Soc. Amer. Proc.* (1938) 3: 37-42.
- (4) CHEPIL, W. S., AND BISAL, F. 1943 A rotary-sieve method for determining the size distribution of soil clods. *Soil Sci.* 56: 95-100.
- (5) CHILDS, E. C. 1940 The use of soil moisture characteristics in soil studies. *Soil Sci.* 50: 239-252.
- (6) COILE, T. S. 1936 Soil samplers. *Soil Sci.* 42: 139-142.
- (7) COLE, R. C., AND EDLEFSEN, N. E. 1935 A sedimentation tube for analyzing water-stable soil aggregates. *Soil Sci.* 40: 473-479.
- (8) COLE, R. C. 1939 Soil macrostructure as affected by cultural treatments. *Hilgardia* 12: 429-472.
- (9) CULPIN, C. 1936 Studies on the relation between cultivation implements, soil structure and the crop: I. *Jour. Agr. Sci.* 26: 22-35.
- (10) CURRY, A. S. 1931 A comparison of methods for determining the volume weight of soils. *Jour. Agr. Res.* 42: 765-772.
- (11) DAY, P. R. Experiments in the use of microscope for study of soil structure. *Soil Sci. Soc. Amer. Proc.* (1948) 13. [In press.]
- (12) FENG, C. L., AND BROWNING, G. M. 1947 Aggregate stability in relation to pore size distribution. *Soil Sci. Soc. Amer. Proc.* (1946) 11: 67-73.
- (13) FREE, G. R., LAMB, J., JR., AND CARLETON, E. A. 1947 Compactibility of certain soils as related to organic matter and erosion. *Jour. Amer. Soc. Agron.* 39: 1068-1072.
- (14) GERDEL, R. W. 1938 Adaptation of the hydrometer method to aggregate analysis of soils. *Jour. Amer. Soc. Agron.* 30: 107-110.
- (15) GISH, R. E., AND BROWNING, G. M. Factors affecting the stability of soil aggregates. *Soil Sci. Soc. Amer. Proc.* (1948) 13. [In press.]
- (16) HAINES, W. B., AND KEEN, B. A. 1928 Studies in soil cultivation: IV. *Jour. Agr. Sci.* 18: 724-733.
- (17) HARPER, H. J., AND VOLK, G. W. 1937 A method for the microscopic examination of the natural structure and pore space in soils. *Soil Sci. Soc. Amer. Proc.* (1936) 1: 39-42.
- (18) HOLMES, A. 1921 Petrographic Methods and Calculations. Murby and Co., London.
- (19) HUTCHINS, L. M. 1926 Oxygen supplying power of the soil. *Plant. Physiol.* 1: 95-150.

- (20) JAMISON, V. C., AND REED, I. F. 1948 Durable asbestos tension tables. *U. S. Dept. Agr., Div. Soil Mangt. and Irrig. Res. Rpt.* 141.
- (21) KOLODNY, L., AND NEAL, O. R. 1942 The use of micro-aggregation or dispersion measurements for following changes in soil structure. *Soil Sci. Soc. Amer. Proc.* (1941) 6: 91-95.
- ✓ (22) KUBIENA, W. 1938 Micropedology. Collegiate Press, Ames, Iowa.
- (23) KUMMER, F. A., AND COOPER, A. W. 1945 Soil porosity determinations with the air picnometer as compared with the tension method. *Agr. Engin.* 26: 21-23.
- (24) LAEMER, R. W., AND SHAW, B. T. 1941 A simple device for measuring noncapillary porosity on an extensive scale. *Jour. Amer. Soc. Agron.* 33: 1003-1008.
- ✓ (25) LUTZ, J. F. 1947 Apparatus for collecting undisturbed soil samples. *Soil Sci.* 64: 399-401.
- ✓ (26) MCCALLA, T. M. 1944 Water-drop method of determining stability of soil structure. *Soil Sci.* 58: 116-122.
- (27) PAGE, J. B. 1948 Advantages of the pressure picnometer for measuring the pore space in soils. *Soil Sci. Soc. Amer. Proc.* (1947) 12: 81-84.
- (28) PAULING, L., WOOD, R. E., AND STURDIVANT, J. H. 1946 An instrument for determining the partial pressure of oxygen in a gas. *Jour. Amer. Chem. Soc.* 68: 775-798.
- ✓ (29) PETERSON, J. B. 1940 A microscopic method of determining the water-stable aggregates in soils. *Soil Sci.* 50: 331-338.
- (30) PROCTOR, R. R. 1933 Fundamental principals of soil compaction. *Engin. News-Rec.* 111: 245-248, 286-289, 348-351, 372-376.
- (31) REDLICH, G. C. 1940 Determination of soil structure by microscopic investigations. *Soil Sci.* 50: 3-13.
- (32) RICHARDS, S. J. 1941 A soil penetrometer. *Soil Sci. Soc. Amer. Proc.* (1941) 6: 104-107.
- (33) RUSSELL, E. J., AND APLEYARD, A. 1915 The atmosphere of the soil. *Jour. Agr. Sci.* 7: 1-48.
- (34) RUSSELL, E. W., AND BALCEREK, W. 1944 The-determination of the volume and air space of soil clods. *Jour. Agr. Sci.* 34: 123-132.
- ✓ (35) RUSSELL, M. B. 1942 Pore-size distribution as a measure of soil structure. *Soil Sci. Soc. Amer. Proc.* (1941) 6: 108-112.
- (36) RUSSELL, M. B., AND FENG, C. L. 1947 Characterization of the stability of soil aggregates. *Soil Sci.* 63: 299-304.
- (37) SCOTT BLAIR, G. W. 1937 Compressibility curves as a quantitative measure of soil tilth. *Jour. Agr. Sci.* 27: 541.
- (38) SCOTT BLAIR, G. W., AND CASHEN, G. M. 1938 Compressibility curves as quantitative measure of soil tilth: II. *Jour. Agr. Sci.* 28: 367-378.
- (39) SHAW, B. T., HAISE, H. R., AND FARNSWORTH, R. B. 1943 Four years experience with a soil penetrometer. *Soil Soc. Sci. Amer. Proc.* (1942) 7: 48-55.
- ✓ (40) STARKEY, R. L., AND WIGHT, K. M. 1945 Anaerobic Corrosion of Iron in Soil. American Gas Assoc., 420 Lexington Ave., New York.
- (41) STONE, A. A., AND WILLIAMS, I. L. 1939 Measurement of soil hardness. *Agr. Eng.* 20: 25-26.
- ✓ (42) TORSTENSSON, G., AND ERIKSSON, S. 1936 A new method for determining the porosity of the soil. *Soil Sci.* 42: 405-417.
- ✓ (43) VEIHMEYER, F. J. 1929 An improved soil-sampling tube. *Soil Sci.* 27: 147.
- (44) YODER, R. A. 1936 A direct method of aggregate analysis of soils and a study of the physical nature of erosion losses. *Jour. Amer. Soc. Agron.* 28: 337.

METHODS OF MEASURING SOIL CONSISTENCY

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Different qualitative definitions and descriptions of soil consistency have been given by soil investigators (8, 19, 40, 52, 55, 60). Russel's description (40) is probably the best known in this country, since it has appeared in both editions of Baver's *Soil Physics* (8, p. 101) and for some time has been in use by the Division of Soil Survey of the U. S. Department of Agriculture.

Within the last 25 years, since the earliest special interest in soil consistency, there has developed a field of systematic study known as *rheology* (9), which is that part of physics dealing with the deformation and flow of matter. The importance of the rheological properties of many industrial and natural materials, the complexities and breadth of the field of rheology, and during late years, the number of its investigators, have led to very many contributions in rheological research (1, pp. 1-92; 48; 50). It therefore seems desirable to think of the subject of soil consistency as part of the broader field of general rheology, within which there is much of interest to the soil physicist.

Of soil consistency, Russel (40) wrote that its manifestations include "the sensations which are evidenced as feel by the fingers of the observer." The point deserves more consideration by workers, who repeatedly estimate other physical properties of soils encountered in the field by their perception and interpretation of the rheological behavior of the material at different moisture contents.

The present discussion of methods of measuring consistency is based on that part of the definition common to the definitions given by the Soil Science Society's 1947 Committee¹ on Terminology (55), the American Society for Testing Materials' 1941 Committee E-1 on Tentative Definitions of Terms Relating to Rheological Properties of Matter (18), and the proposed qualitative usages, in 1947, of both the Society of Rheology and the British Rheologists' Club (14, 18), namely, that consistency is the resistance to deformation of material.

MEASUREMENTS

Many measurements of consistency require elaborate apparatus and it is not possible to consider all of them in the available space. Dynamometer measurements, which are among the most directly interpretable of all consistency measurements, are not discussed here. They are treated with considerable detail by Keen (28) and Baver (8) and in the original papers to which those authors refer.

Russel and his associates considered the agricultural significance of the Atterberg consistency "constants" in 1928. The methods of measurement adopted by them, and used by later workers at the Nebraska Agricultural Experiment Station and elsewhere, are clearly described by Russel and Wehr (41), who also

¹ The committee has adopted the term "consistence" in place of "consistency."

examined the reliability and replicability of the measurements. Of these, the toughness number and solidity number are the only measurements for which numerical expressions of force were obtained. The improvements of Roberts (39) and Bayer (7) are included in a later section of this paper. Russel (42) and Bayer (8) have briefly reviewed the older and many of the more recent methods. Methods of measuring cohesion and stickiness for a limited range in water content are described by Stauffer (53) and Bouyoucos (12).

Measurements of the consistency of suspensions and pastes prepared from clay and other separated fine fractions, made by means of capillary tube, rotating cylinder, and falling sphere viscometers have been omitted. These and other exact types of rheological measurements have been thoroughly treated by Scott Blair (48, 50). Emphasis has been placed in this review on the macrotype of consistency measurement and upon the methods of interpretation necessary for consistency evaluation. Only those methods are included which can be applied to soil samples to or from which no solid constituents have been added or removed.

GROUPING OF METHODS

The methods have been grouped below according to the kind of deformation to which the soil is subjected in the measurement and the type of apparatus used. Groups of methods 2, 3, and, usually, 1 involve violent disturbance of natural structure *throughout the sample under test before measurement*. Groups 6, 7, 8, and 9 involve little or no disturbance of structure before measurement. Measurements of groups 4 and 5 may be carried out on disturbed and remolded samples or, with some adaptation, on sampled cores of otherwise unaltered soil. Measurements made with samples, the original structure of which is undisturbed before measurement, require repeated replication.

<i>Kind of deformation</i>	<i>Apparatus used</i>	<i>Resistance measured</i>
1. Mixing by pug-mill	Plastograph	Torque on motor shaft
2. Plastic flow induced by impact or pressure	Liquid limit or similar device in different forms	None (impact magnitude controlled) or vertical force needed for initiation of flow
3. Lengthening of slender cylinder by rolling	Pachimeter	Vertical resistance through axis and normal to circumference
4. Compression of stationary cylinder	Stress-strain apparatus	Resistance to applied normal load
5. Compression and shearing applied to prism or annulus	Box shear and modified torsion-ring shear apparatus	Resistance to applied normal and shearing stress
6. Shearing of cylindrical core	Transverse shear testing	Resistance to shear normal to long axis
7. Shearing core from surrounding mass in position in field	Rotating vanes	Shearing resistance
8. Compression in position in field	Device for loading soil in place	Resistance to applied normal stress
9. Deformation by penetration	Penetrometer	Resistance to penetration

METHODS

1. Mixing by pug-mill

Rhodes (37) used the Farinograph manufactured by the Brabender Corporation of Duisberg, Germany (13). When used with other materials than flour, the apparatus is called the *plastograph*. A somewhat similar apparatus, designed to measure work input in terms of watt-hours per hundred revolutions of dough-mixing machine blades, was developed and described by Bailey in 1930 (5).

The plastograph consists of a small, synchronous motor-driven pug-mill in which the soil may be mixed with water in any desired proportions. The apparatus is arranged so that the motor frame is free to rotate about the motor drive-shaft, which is in direct alignment with the main drive shaft of the pug-mill. The resistance which the soil-water mixture presents to the rotating blades in the mill exerts an opposing torque on the drive shaft and so tends to rotate the motor frame in the opposite direction. By means of a set of lever arms the torque is transmitted to a weighing device and a recorder. Oscillations of the levers are damped by a dashpot. A recording pen traces a curve on a moving chart which shows, on a curved ordinate, gram-meters resistance as a function of time. Rhodes calls this resistance the *consistency*. During the mixing, water from a burette is added to the soil at a constant rate. Thus the abscissa may be read to determine either time of mixing or soil moisture content. For convenience, the curves are replotted to rectangular coordinates at the end of a run.

The apparatus was used by Rhodes in estimating the quality of soil material for sub-grade use. It was considered to be particularly appropriate for this purpose because of the continual manipulation which such material may receive under traffic and because of the significance of moisture content on subgrade consistency. The curves (fig. 1) reveal a general, slow increase in mechanical resistance (consistency) with water content until, when sufficient water has been added to wet the soil aggregates and cause coherence, a very rapid increase produces a sharp maximum. This is followed, in the finer-textured soils, by a rapid decline in resistance as the soil-water mixture becomes more liquid. It is noteworthy that soils having high consistency as measured in this way are regarded as undesirable, on performance basis, for subgrade use.

The effect of decreasing the proportion of finer than 200-mesh soil material (that is, material passing through 74- μ sieve opening) in mixtures with sand is to diminish both the moisture content corresponding to maximum resistance and the absolute maximum of resistance itself. This is shown in figure 1, in which curves A, B, and C refer, respectively, to natural soils containing 24, 53, and 68 per cent material finer than 74 μ . The materials are described as (A) stable topsoil, (B) moderately unstable clay soil, and (C) very unstable clay soil.

The plastograph measurements are said to permit improved predictions of the needs of soils for added stabilizing agents. Rhodes' examination of the plastograph curves, which he obtained for soils taken as representative of the subgrade soil groups A-1 to A-8, inclusive (35), supplied by the Bureau of Public Roads, showed, however, no simple connection with the results, for the same soils, of other empirical measurements, such as the Atterberg limits and stability under shear. Because of the complicated effect of the rotating arms in the open pug-mill, details of the deformation processes at different soil moisture contents are unknown. Consequently, no exact significance can be attached to the work-expenditure. The work-moisture content function appears to be mainly a reflection of the abundance and composition of the clay fraction and organic matter in the soil. It is affected to a lesser degree by the 140-200-mesh fraction and least of all by the coarser fractions.

2. Plastic flow induced by impact or pressure

According to the original procedure (4, 41) the determination of the liquid limit, or *Fließgrenze*, of Atterberg is not highly standardized.

Roberts (39) improved the determination by using a shallow, flat-bottomed, glass cylinder in place of the curved evaporating dish, and by deforming the soil with weights instead of impacts. Notches in the walls of the cylinder permitted rapid, uniform grooving of the soil paste. The soil was then made to flow by loading with weights so that pressure was transmitted to the soil through a piston-like glass vessel. The critical moisture content was determined by observing incipient flow of paste in the cup. Baver (7), using a basically similar procedure, applied the deforming force by placing the soil vessel on the platform of a Troemner balance and adding weights to the weight support. He found that a force equivalent to 1,000 gm. caused an amount of flow equal to that obtained by the hand method. The moisture content-weight data were then plotted on semilogarithmic paper, and from the straight-line so obtained, Baver proposed interpolation at 1,000 gm. as a means of obtaining the liquid limit. Roberts and Baver reported greatly improved reproducibility of results by means of these procedures.

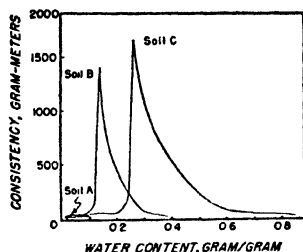


FIG. 1

FIG. 1. PLASTOGRAPH CURVES FOR THREE SOILS

Consistency, as gram-meters of torque, is plotted in relation to soil moisture content. (After Rhodes.)

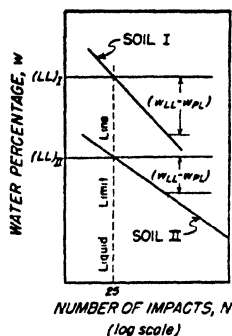


FIG. 2

FIG. 2. IMPACT-MOISTURE-CONTENT CURVES FOR TWO SOILS ON SEMILOGARITHMIC GRAPH
 N is considered proportional to shear resistance of soil. (After Casagrande.)

During an independent, contemporary investigation of the relationship between soil moisture content and resistance of moist soil pastes to deforming impacts, Bodman and Tamachi (10) proposed a simple modification of the procedure, which standardized the magnitude of the impact. This consisted of dropping the vessel containing molded and grooved soil paste from a standard height so that the paste always received the same impact at end of fall. It was also required of every measurement that the volume of plastic flow be held constant and that the shape of the plastic soil mass be simplified so as to avoid slip. A flat-bottomed vessel was used on this account. Having incorporated these changes into the operation described by Atterberg, Bodman and Tamachi then regarded the cumulative number, I , of standard arbitrary impacts as a measure of the force needed to produce a fixed volume of flow in the soil. According to this point of view, I is regarded as an empirical measure of resistance to deformation. The relationship between impact number and moisture content, w , was then investigated for a number of soils and found, over the ranges of moisture content studied, to be given by the expression $I = aw^k$ in which a and k , respectively, are positive and negative constants. Log-log plots of the results provided a suitable means of comparing the moisture contents of different soils at which they offered the same resistance to deformation, that is, the same consistency (called "stiffness" by the authors) and likewise, a means of comparing the consistencies at the same moisture content.²

² The word "stiffness" is now used in rheology in a more quantitative sense than this to define the slope of the linear part of the Bingham flow curve relating stress to rate of plastic flow; it thus corresponds to pseudoviscosity (48, p. 23).

Casagrande (16) followed a similar line of attack to that of Bodman and Tamachi but, while retaining the hemispherical form of vessel holding the soil, he replaced porcelain by metal, standardized the impact to give a small change in momentum, and mechanized the measurement. The liquid limit testing apparatus that he developed has been adopted by Committee D-18 of the American Society for Testing Materials (20, pp. 30-32). For many soils, comparisons between that moisture content found to be present (a) when at the Atterberg liquid limit as determined by the original method of hand measurement and (b) when 25 blows with the Casagrande apparatus were needed to cause the soil to flow, led to the adoption of this number of impacts in the standard apparatus as the specification for the mechanized liquid limit determination.

Casagrande considered the force resisting the deformation of the sides of the groove in the soil paste during the impact treatment to be the shearing resistance of the soil and the number of blows required to close this groove as a relative measure of the shearing resistance at that moisture content. He made many impact—number (N), moisture percentage (w)—measurements with his device. The relationship obtained was given by the equation, $w = -F \log N + C$ for which, graphically, the arithmetical values of w are plotted along the Y -axis and logarithmic values of N along the X -axis, $C =$ a constant, and $-F =$ the slope of the straight line obtained by fitting it to a semilogarithmic plot of the two variables. F is called the flow index. Typical curves³ are shown in figure 2. According to Casagrande's point of view $N \propto S$, in which $S =$ shearing resistance, so that the preceding equation may be written $w = -F \log S + C'$. According to these assumptions the consistencies of soils may be compared by examination of their Casagrande curves. For those soils which are alike in either their plastic range⁴ ($w_{LL} - w_{PL}$) or their flow index, or both, the following classification and interpretations are apparent:

- I. *Soil pastes with same plastic range*—
 - (a) Pastes having the same value of $-F$ undergo the same change in S when dried through their plastic ranges.
 - (b) Pastes having different values of $-F$: the soil paste having the more negative F (the steeper slope) undergoes less change in S with moisture loss and is more easily sheared at the rolling-out limit.
- II. *Soil pastes with same flow index*—
 - (a) Pastes having the same plastic range: see I (a).
 - (b) Pastes having different plastic ranges: the soil paste having the greater plastic range has the higher S at the rolling-out limit.

Casagrande calls the shearing resistance at the plastic limit the "toughness of a soil,"

and defines an "index of toughness" as $T = \frac{(w_{LL} - w_{PL})}{F} = \log \frac{S_{PL}}{S_{LL}}$. This equation is

readily obtained from the preceding by writing equations for w_{LL} and w_{PL} , respectively, in which S_{LL} and S_{PL} are the corresponding Casagrande shearing resistances. The index T results by subtraction and solving for $(w_{LL} - w_{PL})$. The difference $(w_{LL} - w_{PL})$ is the Atterberg plasticity number, also called the "plasticity index." The toughness index as defined by Casagrande is not to be confused with Atterberg's "toughness number" (*Zähigkeitszahl*), which measures the force required to make a sharp, 15°, steel chisel cut 10 mm. into molded soil briquettes when they are slightly in excess of their plastic limit (41).

The arbitrary nature of these two impact methods of examining consistency is emphasized. Also, the limitations of the two equations connecting moisture content and impact number are noted. For example, substitution of $w = 0$ in the equation of Bodman and Tamachi gives $I = \infty$, and in the Casagrande equation gives $N =$ a constant, which is a

³ It is undesirable to call these "flow curves," since this name is generally applied by rheologists to the Bingham flow curves referred to earlier in this section.

⁴ The term "plastic limit" (PL) is used synonymously with "rolling-out limit" (*Ausrollgrenze*) by many workers. It is also called the "lower plastic limit." Similarly, many use the terms "liquid limit" (LL) and "lower liquid limit" (*Fliesgrenze*) synonymously with "upper plastic limit" (Russel).

characteristic of the individual soil. At complete dryness of the molded masses of soil, however, this type of impact method fails as a device for arbitrarily recording stress-deformation relationships. For physical reasons it is unsuited to exact calculation of the force producing deformation. The same stiffness, flow index, or toughness values could not be expected from different apparatus and measurement procedures. Sandy soils which, nevertheless, show a certain amount of plastic deformation are unsuited for examination by either of the methods. When a curved containing vessel is used, there is particular danger of premature closing of the groove-shaped opening due to slippage of the soil on the curved surface of the container. Despite their empirical nature, however, the methods are of value for comparative purposes and in rapid estimates of consistency.

Measurements of both liquid and plastic limits are considered important by highway, airport, and foundation construction engineers in estimating the bearing strength of soils under load. The U. S. Public Roads Administration has prepared a soil classification system (34, 35) in which much weight is given to the consistency of soils at different moisture contents as manifested by these two, arbitrary "constants." Attention has therefore been given to their determination by the Public Roads Administration, American Association of State Highway Officials, and the American Society for Testing Materials: Committee on Soils for Engineering Purposes (Committee D-18). The standardized methods of measurement are described in detail in the Society's "Procedures for Testing Soils—1944" (6, pp. 30-34).

3. Lengthening of slender cylinder by rolling

Schofield and Scott Blair (43, 45) found that the applied weight necessary to begin the lengthening of a slender cylinder of wet soil was simply connected with radius and length of cylinder and differed in a significant way from one soil to another. The determination is considered to measure the "heaviness" of soil samples. It requires a special apparatus, named by its authors a "pachimeter." The first part of the name is derived from the Greek word "pachys," which, when applied to soils, corresponds closely in meaning to our own word "heavy."

The machine consists essentially of two horizontal plates, an upper one of glass with a lightly ground lower surface, and a lower one of wood. The plates are made to move reciprocally at a constant rate of about 30 reciprocations per minute and to cause a small cylinder of moistened, well-washed and molded soil to rotate completely about its long axis when placed between them.

The soil is first brought to its sticky-point moisture content, which degree of wetness is regarded by the authors as the moisture content of maximum plasticity. If the moistened soil feels very gritty, it must first be passed through a 100-mesh sieve. For obvious reasons, a high diameter ratio: soil particle/molded soil cylinder, is objectionable. The soil mass is then molded and given a preliminary rolling and trimming to form a cylinder of standard thickness and length (cylindrical dimensions of 10 mm. in length by 1.78 mm. in diameter were used with the original machine). The finished cylinder is then rolled, mechanically, back and forth between the plates, while a continually increasing load is applied to the upper plate and the shape and length of the cylinder are kept under close observation. Lengthening is detected by use of a movable millimeter scale on the glass plate. The end point is reached when the soil cylinder just begins to lengthen. At that time the applied weight, W_u , is recorded and the measurement is complete. The weight, in grams, is called the "critical rolling weight."

The critical weight has been shown to be proportional, as might be expected, to the cylinder radius, so that $W_u = kLr$, in which L = length, r = radius, and k = a constant which, for small specimens of a given soil, is independent of size of cylinder. Correction of W_u to that equivalent to the standard radius of 1 mm. is recommended. With a cylinder of radius, r_u , other than 1 mm., since L is constant until lengthening begins, the corrected weight W is obtained from the uncorrected weight, W_u , by the relationship:

$W = \frac{r}{r_u} W_u$. If the position of the weight is not immediately above the soil cylinder it is necessary, in addition, to correct for its position on the upper plate. For the authors' apparatus the final correction factor due to combined radius and weight moment corrections was 1.07. Values of W for a wide variety of soils have been reported to range between about 5 and 50 gm. High percentage accuracy is not claimed, but this is in part compensated by the wide range in W . Soils having clay contents of less than about 10 to 15 per cent cannot well be tested in the apparatus without prior separation of some of the coarse particles. This is objectionable because it alters the soil. Development of flattening and eccentricity in the cylinders is likely with saline and alkaline soils, but it is said that this can generally be corrected by raising the upper plate, touching the sample with the finger, and again rolling.

Critical rolling weights are correlated with clay content. Soils of different types, however, commonly show widely different values for a given amount of clay and so reflect soil properties which may be ascribed to the composition and other peculiarities of the clay. The critical weights were found to be closely related to drawbar-pull values for a certain field on the Rothamsted farm.

4. Compression of stationary cylinder

The "friability" of soil has been described as the tendency of a mass of unconfined soil in bulk to crumble and break down, under applied stress, into smaller fragments, aggregates, and individual particles. The term thus refers to an inherent weakness in resisting deformation.

Christensen (17) proposed a quantitative index of friability, the calculation of which depends upon a series of stress-strain measurements of the soil concerned. A suitable and relatively simple machine was constructed for this purpose at the Utah Agricultural Experiment Station.⁵ It consists of a combination of two lever arms, one above the other, on the calibrated end of the upper one of which, weights are placed, the system being arranged so as to develop a mechanical advantage of 100 to 1 over the resistance to deformation exerted by the test specimen of soil. The cylindrical soil specimen is placed so as to rest between a bearing plate fixed on the lower lever arm and a snugly adjusted swivel-joint plate above. The latter is attached to a screw crank mounted on framework and independent of lever arms.

With knowledge of the cross-sectional area and initial height, h , of the soil specimen, the measurements begin with addition of weights to the upper lever arm. These are made just sufficient to diminish the height of the cylinder by 0.5 mm. (Δh), automatic provision being made for this exact amount of compression. One pair of stress-strain values is thus obtained. The weights on the upper lever arm are then removed, the screw crank is adjusted to maintain the specimen under uniform pressure, and a second pair of values is obtained as described for the first. This procedure may be replicated many times, the number possible depending on the magnitude of the planned height decrement, Δh , and the properties of the soil. A series of pairs of unit stress (= pressure in kgm./cm.²) and unit strain ($\Delta h/h$) values provide the necessary data for calculating the friability of a given soil at a given moisture content.

Soil cylinders 3 cm. long by 2.5 cm. in diameter were found most suitable for the measurements. They are prepared from previously sieved soil, moistened and mixed to form a stiff mortar, and molded in a steel cylinder. Drying is done slowly in a dark chamber to avoid cracking of fine-textured soils. Cracked specimens are discarded.

Figure 3, taken from Christensen's data, shows a set of four stress-strain curves for the same soil at four different moisture contents. Ten pairs of stress and strain values were obtained for the construction of each curve. The yield point Y is shown in figure 3 for

⁵ A somewhat similar apparatus has been used by Vassilenko and Setzinsky (61) with cores from undisturbed soil columns.

each of the curves *a*, *b* and *c*, for which it is seen to correspond to the point of maximum stress. For the same soil, in the very moist and plastic state shown by curve *d*, *Y* occurs at a unit stress so small that it is undeterminable by this method.

From stress-strain measurements for two soils and their mixtures at many different water contents, Christensen concluded that the maximum bearing strength-moisture content relationships could be expressed by the equation $S = S_0 e^{-kw}$, wherein S = maximum unit stress (= pressure at yield point) at any moisture content w , S_0 = maximum unit stress for $w = 0$, and k = a constant. The soil constants S_0 and k must be determined experimentally.

The friability, F_m , is defined in general as $F_m = \frac{\text{unit deformation at yield point}}{\text{work of deformation to yield point}}$. Work of deformation up to the yield point is obtainable from the stress-strain curve by

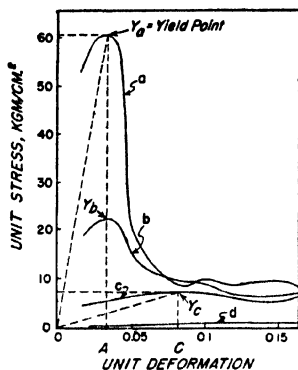


FIG. 3

FIG. 3. STRESS-STRAIN CURVES USED IN CALCULATION OF FRIABILITY INDEXES

The curves represent the behavior of a single soil at four different moisture contents: $a = 0$, $b = 8.3$, $c = 16.6$, and $d = 25.0$ per cent water. (After Christensen.)

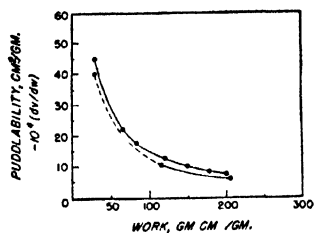


FIG. 4

FIG. 4. PUDDLABILITY-WORK FUNCTIONS FOR YOLO LOAM AT FIELD CAPACITY

Upper curve represents relationships during application of normal stress alone; lower curve refers to relationships at the beginning of applied shearing stress. (After Bodman and Rubin.)

integration between zero strain and the strain at the yield point. As a sufficiently close approximation to this work value, however, Christensen proposed use of half the product of the unit stress and unit strain coordinates taken at the yield point. See areas OY_aA and OY_cC , figure 3, for approximate work of deformation to yield point for the same soil material at moisture contents $w = 0$ and $w = 16.6$ per cent, respectively. Thus, $F_m =$

$$\frac{\sigma_y}{\frac{1}{2}S_y\sigma_y} = \frac{2}{S_y} \text{ in which } \sigma = \text{unit strain, } S = \text{unit stress, and the subscript } y \text{ indicates that}$$

the magnitudes are to be taken at the yield point. Since $S = 2/F$, the equation $F_m = \frac{2}{S_y}$

may be used for calculating the friability, F , at any moisture percentage w by substitution in the first equation to give $F = F_0 e^{kw}$. Expressions of soil friability can be obtained from

the equation $F_m = \frac{2}{S_y}$; however, for valid comparison between different soils it appears

preferable to use the equation $F = F_0 e^{kw}$, in which are substituted for w not the arbitrary but the most appropriate comparable, moisture percentages. These may well be chosen, for the soils concerned, from suitable points on the tension-moisture content, or other energy-moisture content curves. It should be noticed that as tested by Christensen, the

soils are in a preworked, molded, state. This avoids both the variability due to heterogeneity and the difficulty, inherent in many soils *in situ*, of obtaining intact, natural cores. On the other hand, it introduces a serious difficulty of interpretation for field conditions, although the method can be used with carefully collected cores of firm soil. The notion of friability, moreover, is not easily connected with the plastic flow displayed by soil materials at high moisture contents. Finally, as pointed out by its originator, unit strain as measured by this method is, because of lateral deformation, only an approximation for materials that crumble under compressive stress.

Triaxial stress-deformation measurements of consistency of soil cores are described in the A.S.T.M. publications (3, 6). [See also Krynine (30) and Pokrowsky *et al.* (33).]

5. Compression and shearing of prism or annulus

Eight contributions published in the A.S.T.M. "Procedures for Testing Soils—1944" (6) describe suggested methods for measuring shearing resistance. Three (6, 20, 31) require relatively simple apparatus, designed for direct shear measurements by translatory shear of prism-shaped masses.

Essential parts of the apparatus are: (a) a rectangular shear box in which either disturbed or, with adaptation, undisturbed soil samples may be placed, (b) a device for applying a known amount of stress tangential to a plane passing between the upper and lower halves of the box and another for applying known stress normal to that plane, (c) gauges for measuring the vertical and horizontal deformation of the soil. The shear box is divided horizontally into an upper and a lower frame arranged for shearing a body of soil contained in it. This is brought about by an applied tangential stress which results when the upper and lower frames of the box are moved, relatively to each other, in opposite horizontal directions against the shearing resistance of the soil, a vertical force pushing them together meanwhile. As used in soil mechanics testing, porous stones are placed above and below the test sample although piezometers are not used in these three methods. The addition of strain-control or stress-control mechanisms increases the significance of the measurements but necessitates elaboration of the apparatus.

Measurements under strain control should be made at deformation rates of not less than 0.02 or more than 0.10 inch/minute (20) and at 0.04 inch/minute (6). If stress-control apparatus is used, Converse recommends that stress be applied at a speed which will insure completion of the test in less than 10 minutes. Amounts of normal load depend on the purpose of the test. With such rapid tests, attainment of equilibrium is uncertain.

The results are commonly plotted, for vertical stress parameters, with shear stresses as ordinates and shear displacements as abscissas. Converse suggests that the shearing strength of the soil be determined from the shearing stress at that point where the load-deformation curve breaks. Vertical and shearing stresses are calculated from the equations

$S_v = \frac{L_v}{a}$, and $S_s = \frac{L_h}{a}$, in which S_v = vertical stress, S_s = shearing stress, L_v = vertical load, L_h = horizontal load, and a = horizontal area of soil between upper and lower sections of the box.

Krynine (30, pp. 181-183) discusses important considerations in connection with shear measurements in soils. These are presented from the point of view of one primarily interested in shearing strengths for use in structural design in which fairly high normal stresses and high soil moisture contents are encountered. Water-saturated soils and pressures in excess of 30 to 40 pounds/square inch are not commonly of interest to the soil physicist concerned with soil consistency as it may affect agricultural operations and processes, although the rigorous analytical treatments of the soil engineer well repay study.

Other methods of measuring shearing resistance are described in the A.S.T.M. Symposium on Shear Testing (3).

Bodman and Rubin have made use of a specially adapted form of Hvorslev's (27) ring-shearing apparatus, which they described in connection with soil puddling measurements (11). Any attempt at direct physical measurement of puddling is a problem in soil con-

sistency and involves measurement of stress and strain. The apparatus thus included provision for measuring compressive and tangential stresses and changes in apparent specific volume of the soil. The decrease in specific volume of a confined mass of soil was considered as a measure of the amount of puddling.

Loose, moist soil material in a condition similar to that of the soil in a freshly prepared seedbed was placed in a ring-shaped cylinder for the puddling treatment. Stresses were applied in different ways. The most significant so far used for the puddling measurements involved application of slowly increasing values of normal stress up to some suitable, terminal value, followed by slowly increasing tangential stress until the attainment of what has been tentatively regarded as the maximum shearing resistance of the soil. Care was taken closely to approximate equilibrium values for stress and strain relationships. From knowledge of the time rate of application of stress and corresponding specific volume measurements, it was possible, from graphs of specific-volume-time curves, to integrate for the work of puddling in gram-centimeters per gram of soil. The notion of "puddlability" was introduced during investigation to describe the ratio of change in specific volume, v , to corresponding work expenditure, w . Puddlability = $-\frac{dv}{dw}$, the minus sign being

introduced to represent by positive numbers the susceptibility to puddling, dv itself being negative. According to this definition, puddlability is a measure of the consistency of a soil. The puddlability-work functions of Yolo loam as measured by this method are shown in figure 4. During the puddling the absolute decreases in specific volume were from 1.37 to 0.71 cc./gm.

Stress calculations in these compressions and shearings of soil prisms and rings make no allowance for changes in bearing area due to aggregate breakdown during the measurement, nor are microvolume and pore-size distribution changes measured according to present apparatus design.

Ward (63) very recently described a concentric cylinder viscometer adapted from an earlier design by Ungar (59). It consists of a stationary inner, and rotatable outer, cylinder, each equipped with teeth. The material for test exists as a hollow cylindrical mass between. An end-plate at one end of the cylinders can be removed and the paste examined and photographed from time to time for angular displacement. Ward has obtained valuable Bingham flow curves relating shearing rates and stresses for homogeneous pastes. The apparatus and certain special features of the method may be adaptable for use with specially cut segments of natural soil.

6. Shearing of cylindrical core

Housel (25) uses a simple transverse shear test for soils, the procedure for which is based on the idea that the measurement of shearing resistance can be reduced to a determination of the yield value. The method as designed has the advantage that measurement is made on a core cut out of the undisturbed soil mass rather than on a recompacted sample.

The cylindrical soil core, 1½ inch diameter by about 10 inches long, is taken in a stainless steel tube fitted with a sectional stainless steel liner. The tube has a detachable chrome-molybdenum cutting edge. Both cutting edge and liner are 1½ inch inside diameter. The liner containing the soil core may be removed from the tube, after sampling, without disturbance of the core. The liner is divided into four sections: a 1-inch length between two adjacent 3-inch lengths, and one 2.9-inch length. Soil contained in the extra 2.9-inch section is used for supplementary tests. Steel liner and core are placed in a brass cylinder, sealed with paraffin, and taken to the laboratory for the test.

To make the shear test, that part of the steel liner and core consisting of the 1-inch and adjacent 3-inch sections is transferred intact from the brass cylinder to a supporting cylinder resting horizontally in a saddle made of two parallel angle irons. The saddle is mounted at the edge of a rigid framework. During the transfer of sections to the supporting cylinder the 1-inch section must be aligned with a corresponding, removable section of the

supporting cylinder. This removable section of the support is arranged to allow for suspension from it of an added load which will impart tangential stress, at right angles to its cylindrical axis, at both ends of the 1-inch section of the soil core. A dial gauge reading to 0.001 inch, mounted vertically above, and with tip resting on, the 1-inch supporting section, records the shearing displacement.

The load is applied in definite increments of static load, the magnitude of each increment being approximately equal to one-fifth of the estimated yield value. The load is held constant for 10 minutes after each increment so that frequent deformation readings can be taken between load increases. A deformation-time curve is then plotted for each load. The load is increased in this way until sufficient has been added to cause shear failure.

Typical results for a transverse shear test on a core of clay are shown in figure 5a, in which the curves relate gauge deflections to time duration of maintenance of constant applied load. Each curve is labeled to show the number of units of tangential stress applied; 1 unit of stress = 0.416 pound/square inch. Note the fairly rapid approach, with time, to a constant gauge reading, that is, to zero time rate of displacement, for tangential stresses 1, 2, and 3.

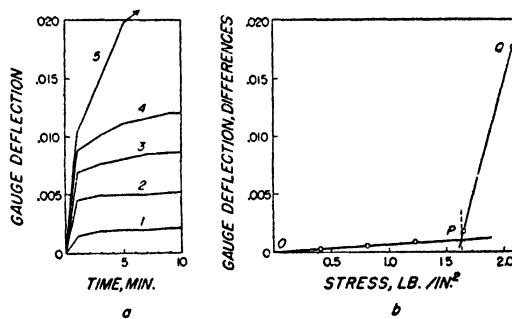


FIG. 5. TYPES OF DIAGRAMS OBTAINED DURING TRANSVERSE SHEAR TESTS ILLUSTRATING METHOD OF CALCULATING YIELD POINTS

(Adapted from Housel.)

Figure 5b shows gauge-deflection differences between the end of the third and tenth minutes of maintenance of a given tangential stress application. The curve in this graph may be regarded as an approximation to a rate of deformation-applied stress curve. The positions of the first three points, for the stresses 0.42, 0.83, 1.25 pounds/square inch, respectively, suggest a linear relation between deformation rates and the three low stresses. At some stress above 1.25 pounds/square inch the curve bends sharply upward, representing a rapid increase of rate of deformation with increased tangential stress. Housel regarded the earlier, flat part of the curve in figure 5b, between 0 and 1.25 pounds/square inch, as indicating an approach to elastic behavior. The increase in rate of deformation produced by tangential stresses of 1.66 and 2.08 pounds/square inch he considered as indication of plastic flow. To obtain an expression for the shearing resistance, the curve is broken into two linear parts, and the tangential stress corresponding to the intersection of these parts is taken as the yield point. The yield point, in turn, is taken as the shearing resistance corresponding to the soil and conditions in which it was tested. This is 1.63 pounds/square inch for the soil under consideration.

Because of the simplicity of the apparatus and procedure, and its adaptation to undisturbed soil samples, Housel's method has much to commend it. The usual sampling and measurement difficulties are to be expected in stony and gravelly soils, however. Because of their high friability, freshly cultivated surface soils likewise would commonly be unsuited to this treatment. The method is especially fitted, in its mechanical features, for testing semiconsolidated soil material.

7. Shearing core from surrounding mass in position in field

An apparatus and a method for determining the resistance to shear of undisturbed soil in place have recently been described by Carlson (15). It is understood that a similar method was in process of development elsewhere during and before the war.⁶ The method is still in an early stage of development but appears to have much promise for use not only in deep foundation material, for which it was designed, but also in both surface and sub-surface of agricultural soils.

The method depends on the application of torque to a vertical shaft on which four vertical, radial, rectangular metal vanes are rigidly mounted and made to shear through a mass of soil, *in situ*, into which they have first been driven with the minimum of soil disturbance. Stress is applied manually in the present state of the apparatus, but mechanical elaboration should be possible, if desired, so that considerable control of stress and strain could be developed.

The apparatus consists of an extensible tubular casing fitted inside with guides and a bushing through which passes a vertical shaft. The vanes are attached at the lower end, below the tube, and a cross member, which provides two lever arms to which stress is applied, is attached to the upper end of the shaft. A "turning handle," the axis of which is aligned with axis of vertical shaft, rests on a bearing attached to the head of the casing. It is connected to the lever arms by means of two spring balances so that rotation of the turning handle tends to rotate the shaft. The required stress may be read on the balance indicators.

Any attempt to impart a rotary motion to the vanes, about the axis of the vertical shaft on which they are mounted, is opposed by the shearing resistance of the soil. Thus a torque, M , is developed which must be overcome by force applied by the operator to the lever arms. This is accomplished by slow turning of the handle from which the applied force is transmitted to one end of each of the lever arms. The driving torque thus applied transmits a shearing stress, through the vanes, to the soil. The handle is turned at a constant low velocity, which should not exceed $0.1^\circ/\text{second}$. In hand operation, the velocity is controlled by observation of a watch and large protractor. The latter is mounted on the head of the casing just below the turning handle. During a shearing test the turning motion is continued by the operator until after the spring balances have indicated the application of a maximum force. Turning is then stopped.

Investigation of the shape of the surface of soil failure after shear, brought about by a two-vaned instrument, has shown this surface to be almost cylindrical. If it is assumed, at the time of reading the maximum moment (M_{max}) of applied force, all of which is supposed to be spent in shearing the soil, that (a) the shearing resistance is fully developed over the entire surface of the body of soil surrounded by the surface of failure, (b) the surface of failure is right-cylindrical in shape, and (c) the torque, from friction, on the vertical turning shaft is negligible, then the shearing resistance is calculated as follows: Let $M_{max} = M_v + 2M_H$ in which M_v = torque due to shearing resistance over vertical part of cylindrical surface and M_H = torque due to shearing resistance at each of the upper and lower horizontal planes of cylindrical surface. Also, if S = shearing resistance of soil per unit area, h = vertical length of each vane, r = horizontal, or radial, length of each vane (= radius of cylinder contained by surface of failure) radius of turning rod being neglected, $D = 2r$, $S dA$ = shearing resistance for each element of surface area, then

$M_v = 2\pi rhSr = \frac{\pi}{2} D^2 hS$. For each end, $dA = 2\pi r dr$, so that $2\pi r dr Sr$ = torque due to any

element of horizontal area, $M_H = 2\pi S \int_0^r r^2 dr = \frac{\pi}{12} SD^3$, $M_{max} = S \left(\frac{\pi h D^3}{2} + \frac{\pi D^3}{6} \right) = Sk'$,

and $S = M_{max} / k$, in which k = a constant of the apparatus defined by the reciprocal of the sum of the bracketed terms. The shearing resistance, S , is expressed by Carlson in kilograms per square centimeter.

⁶ Private communication by G. D. Aitchison, Div. of Soils, C.S.I.R., Australia.

The moment at any instant is given by the equation $M = (P_1 + P_2)A \cos \alpha$ in which P_1 and P_2 are the readings, respectively, of the two spring balances connecting the turning arm and the lever arm; A is the distance between shaft axis and point of attachment of spring balance to turning handle; 2α = angle made by handle and lever arm. This equation corrects for the varying moment caused by increase of (2α) as turning proceeds. $\cos \alpha$ must be determined experimentally for different readings of the spring balances. To calculate M_{max} , the three readings P_1 , P_2 , and α are all obtained at their maxima.

The apparatus is brought into position for a measurement by driving the casing, vertical shaft, and attached vanes through the soil which overlies that to be tested. Since the bottom of the casing is closed by a guide plate and bushing around the shaft, there may be soil compression ahead of the tube. This objection may be without significance in very wet, fine-textured soils of low density, and in any case the danger of such disturbance of the test region is in part overcome by provision for advancing the vanes yet deeper, and into the test region, after the casing is placed. Placement could be improved by drilling out or excavating the overlying soil to the required depth for test.

According to Carlson, who has used the method in undisturbed clays, the maximum torsional moment, when measured at the velocity 0.1°/second, exceeds by less than 5 per cent the value obtained by extrapolating the moment-turning velocity curve to zero. For soil between the depths of about 2 and 6 m. he obtained good agreement of results with those of unconfined compression and cone methods of measuring shearing strength. At greater depths the rotating vane method gave higher results. The apparatus could presumably be built of different strengths and arranged for adaptation to different soil conditions.

8. Compression in position in field

Scott Blair and Cashen (46, 47, 49) designed both field and laboratory apparatus for measuring the compressibility of cultivated soils during an investigation of soil tilth. Their interpretation of the stress-strain curves depended upon experiments with both kinds of apparatus, but only that used on soil in the field is described here.

The apparatus is built about a tetrahedral frame of iron which rests on the ground. On two of the legs a windlass is fixed, a little less than midway between apex and base. From its apex the frame supports a pulley, over which passes a short cable attached at one end to the windlass and at the other to a spring balance. From a point just above its center of gravity a cylindrical weight of 230 pounds, with circular lower surface of 177 square inches, is attached to the balance. By turning the windlass crank, none, or any fraction, of the weight can be made to rest on the ground or be supported by the balance. The spring balance reading, subtracted from 230 pounds, gives the load on the ground. A duralumin rod is pivoted at one end to the suspension between balance and weight. By means of an independently supported fulcrum, its far, pointed end moves over a millimeter scale fixed on another independent support. To reduce pressure of apparatus on the soil around the experimental area and ensure stability, 8-inch metal discs are attached to the three lower corners of the framework and to the fulcrum and scale stands. Elastic give in the apparatus was found to be extremely small.

Load increments are applied at $\frac{1}{4}$ -minute intervals, and the amount of soil deformation below the load is obtained by reading the position of pointer on a scale. Immediately before each increment the load, L , and the deformation, σ , are recorded simultaneously by two operators. By turning the windlass and taking load and deformation readings at constant time intervals, data are obtained for a stress-strain diagram.

During design, Scott Blair kept in mind the importance of maintaining a large ratio between the possible bearing-area beneath the load and the supporting area of the soil lumps upon which the load might rest. In its final form the apparatus appears to have been a compromise between a desire for fairly large pressures, a wide bearing-area ratio, and portability of equipment.

(21), Hénin (23), Reed (36), Richards (38), Shaw, Haise and Farnsworth (51), and others. Richards' penetrometer has the advantage of simplicity of design and comparatively inexpensive construction. It consists of a portable, galvanized-iron framework to the top of which a crank is attached. Two horizontal cross-members, joined by two vertical coil-springs, can move freely up and down on the framework. To the upper of these the probe-rod is fixed. It is allowed to clear the lower cross-member by means of a cross-over fixture on the latter, whence it extends downward through the platform to the soil surface. The penetrometer point is forced into the soil by turning of the crank. This rolls up a branched, wire cable. By means of a system of pulleys, the cable pulls the lower cross-member downward, thereby extending the springs attached to cross piece at top of the probe-rod and so forces the probe into the soil. Force transmitted to the probe is through the springs, and their elongation measures the force used in overcoming resistance of the soil. A drum with graph paper is mounted on the probe-rod and is made to rotate with the same linear velocity as that of the downward moving probe. A trace is made upon it by a pen, which is supported by the lower cross-member. A counterweight makes it unnecessary to correct for weight of probe and spring attachments. As the springs are stretched, the pen moves down over the paper so that a corrected force-depth graph is plotted directly.

Speed control, essential for accurate resistance measurements, is said to be possible between 2 and 4 inches/minute, despite the manual operation for which the machine is designed. Stronger springs and additional weight on the platform are supplied for probing hard soils.

Figure 7a presents a typical graph obtained directly by Richards' penetrometer. The importance of knowledge of soil moisture status during resistance measurements is shown in figure 7b by the tensiometer curve, tension against time, also measured by Richards. It is to be noted that measurements 4, 5, 6, and 7, in (a), were taken during a drying period in the soil moisture cycle. An earlier measurement, No. 3 (curve not reproduced) was separated in time from No. 4 by 11 days, during which there were three rainstorms. Curve No. 3 is almost coincident with curve No. 6 and, as seen from figure 7, was obtained during a general wetting period.

The influence of soil water content on probe resistance is also evidenced by the ingenious device of Allyn and Work (2), who used the mechanical resistance to penetration as an index of the amount of soil water present in a form available for plant growth.

The Veihmeyer soil tube (62) and hammer have frequently been used in California as an impact-type soil probe. The diameter increase just above the cylindrical cutting edge of the tube largely eliminates friction between soil core and tube interior during vertically downward penetration. The soil tube has the advantage that, with care, data may be obtained simultaneously for three physical properties of the soil *in situ*. These are: resistance to penetration, moisture content, and apparent (bulk) density. For these combined measurements it is most useful within the uppermost 3 to 5 feet of firm, stone- and gravel-free soils which are not excessively sandy and are at about their field-moisture capacity.

The shape, size, composition, and condition of the point or cutting edge of a soil probe all affect the results obtained. The zone of compression made by most probes during penetration is presumably somewhat annular in plan form, particularly with a circular cutting edge, and cordoid in vertical section, particularly with a pointed probe. Undoubtedly the volume and shape of the compressed area are affected by the particle-size distribution as well as many other soil properties, including moisture content and local heterogeneity. Shaw *et al.* (51) emphasized the advisability of measuring, so far as possible, all other soil variables at the time of penetrometer measurements.

The penetrometer method of estimating soil consistency is most suitable for rapid comparison of soils for which the soil properties lie within a narrow range of variability.

Hénin (24) analyzed the geometry of the types of penetrometer curves for $F_x = f(x)$, in which F_x = force resisting penetration at any soil depth x , and $f(x)$ = a function of x .

To provide what were regarded as extreme soil conditions, two different materials were set up, for each of which graphs of resistance versus depth were obtained with a penetrom-

ter. Material (i) was chosen to set a standard for the condition of soil looseness and ease of workability (*sol meuble*); the condition was created by use of unconsolidated Fontainebleau sand, chiefly composed of sand grains ranging in diameter from 0.2 to 0.4 mm. Material (ii) was chosen to furnish a compact state (*sol compact*), which was established by packing in a box a moist soil containing about 16 per cent clay. Figure 8a shows the depth resistance relationships for these two conditions. Curve (i), line OB , is for loose condition, and curve (ii), line OCB , is for the compact. Note that point B is at the intersection of curves (i) and (ii).

Curves (i) and (ii) are replotted in figure 8b, curve (ii) being there shown in an idealized form. The curves of figure 8b were then used to demonstrate the development of an "index of looseness" (*indice d'ameublissement*), by means of which soil consistence may be judged. The central idea in Hénin's index is that the linear relationship, $F_x = cx$, is characteristic of a penetrometer diagram for a loose, easily workable soil and that, correspondingly, $\frac{1}{2}F_x x$ is the characteristic expression for the amount of work expended in causing pene-

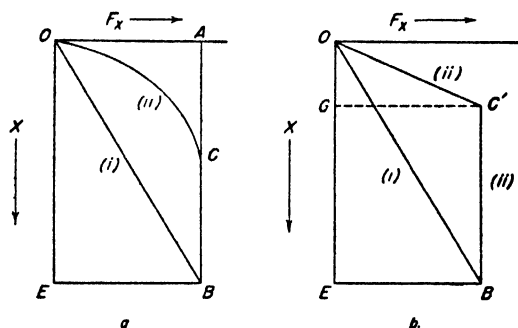


FIG. 8. FORCE OF RESISTANCE-DEPTH CURVES FOR (i) LOOSE AND (ii) COMPACT SOIL CONDITIONS

Part (a) is reconstructed in (b) in idealized form, which also facilitates estimation of area under curve (ii). Distance OG = length of penetrometer point. (After Hénin.)

tration to the depth x in such soil. The work expression is immediately apparent from consideration of curve (i) in figure 8. It should be noted that the constant, c , may vary from one soil to another.

According to Hénin, the consistency characteristics of any soil may now be expressed by comparing the *actual* work expenditure in forcing the penetrometer point into the soil to a given depth, with the *theoretical* work expenditure had the soil yielded a resistance curve of the form $F_x = cx$ over the same depth range. F_x must be obtained by making resistance (or work) measurements over a few depth increments just above and below the depth x . Hénin's index, A , is thus defined:

$$A = \frac{\text{work of penetration to depth } x \text{ for the relationship } F_x = cx}{\text{observed work of penetration to depth } x}.$$

From figure 8a, for example, we have as index for the compact soil (ii)

$$A_{(ii)} = \frac{\text{area } OBE}{\text{area } OCBE} = \frac{\frac{1}{2}F_x x}{\sum_x f(x)\Delta x}$$

The probable minimum value of A for a uniformly compact soil may be calculated from figure 8b. For soil condition (ii), $A = \frac{\text{area } OBE}{\text{area } OC'BEG}$, the depth OG being equal to the length of the lower cone-shaped part of the penetrometer point. For penetration depths of a

foot or so, and with points no greater than a few centimeters in length, it is probable that this minimum will be about 0.50. Hénin appears to have applied the calculations to the cultivation zone. He calculated a minimum value of 0.57 for a penetration depth of 20 cm. and a conical point 4.5 cm. long and drew these conclusions with respect to the index A :

Index Value	Condition of Soil
$A < 0.57$	Soil is harder at surface than below (for example, surface crust caused by rain)
$A = 0.57$	Soil is uniformly compact throughout
$A = 1$	Loose, easily worked soil
$A > 1$	Hard layer present beneath surface

In moist soils, high A values indicate a soil that will remain friable on drying; low values mean that the soil will become harder when dry.

Trials made with two different penetrometers led to the conclusion that calculation of index A is independent of apparatus. This was supported by calculations of A for numerous soils studied in many different places by different investigators. Some of these soils had received measurements before and after spading and gyrotilling. Tillage of a given soil increased its A value. Hénin has pointed out that the indexes gave independent information in agreement with the conclusions of those who made the penetrometer measurements.

It is evident that two different soils, if examined at comparable moisture contents, may have similar bulk densities although the dominant size, shape, and consistency of individual particles and aggregates may differ considerably. It is to be expected that Hénin's constant c in the resistance equation will also be affected. The dimensionless index A , itself a function of c , thus appears to be better suited for comparing intermittent measurements of the consistency of a given field soil, in relation to time, treatment, and moisture contents, than for comparing the consistency of two distinctly different soils. If, on the other hand, F_x for one soil $\cong F_x$ for another soil, x being the same in both cases, the respective indexes will be more nearly comparable, provided the effective moisture contents are similar in the two soils.

REFERENCES

- (1) ALFREY, T., JR. 1948 Mechanical Behavior of High Polymers. New York. Interscience Publishers, Inc., New York.
- (2) ALLYN, R. B., AND WORK, R. A. 1941 The availameter and its use in soil moisture control: I. *Soil Sci.* 51: 307-319.
- (3) American Society for Testing Materials 1939 Symposium on shear testing of soils. *Amer. Soc. Testing Mater. Proc.* 39: 999-1122.
- (4) ATTERBERG, A. 1912 Die Konsistenz und die Bindigkeit der Boden. *Internat. Mitt. Bodenk.* 2: 149-189. (See also other articles by this author and associates in vols. 1, 3, 4, and 6 of this periodical.)
- (5) BAILEY, C. H. 1930 A new method for measuring the relative plasticity of pastes and doughs. *Jour. Rheol.* 1: 429-432.
- (6) BARBER, E. S. 1944 Suggested method of test for direct shear in soil. In *Procedures for Testing Soils*. Amer. Soc. Testing Mater., Philadelphia.
- (7) BAVER, L. D. 1932 The use of the Troemner balance for measuring the upper plastic limit of soils. *Jour. Amer. Soc. Agron.* 24: 686-690.
- (8) BAVER, L. D. 1948 Soil Physics, ed. 2., Chapt. IV. John Wiley and Sons, New York.
- (9) BINGHAM, E. C. 1929 Some fundamental definitions of rheology. *Jour. Rheol.* 1: 507-516.
- (10) BODMAN, G. B., AND TAMACHI, M. 1930 Studies of soils in the plastic state. *Soil Sci.* 30: 175-195.
- (11) BODMAN, G. B., AND RUBIN, J. Soil puddling. *Soil Sci. Soc. Amer. Proc.* 13. (In press.)

- (12) BOUYOUCOS, G. J. 1932 A simple and rapid method for measuring the stickiness of soils. *Soil Sci.* 34: 393-401.
- (13) BRABENDER, C. W. 1934 Six years farinography. *Cereal Chem.* 11: 586-597.
- (14) British Rheologists Club 1947 The meaning and use of certain rheological terms. *Rheol. Bul.* 18: 8-13. (Published by the American Institute of Physics, New York.)
- (15) CARLSON, L. 1948 Determination *in situ* of the shear strength of undisturbed clay by means of a rotating auger. *Second Internatl. Conf. Soil Mechanics and Found. Engin. Proc.* 1: 265-270.
- (16) CASAGRANDE, A. 1932 Research on the Atterberg limit of soils. *Pub. Roads* 13: 121-130, 136.
- (17) CHRISTENSEN, O. 1930 An index of friability of soils. *Soil Sci.* 29: 119-135.
- (18) Committee on Definitions 1941 A report on rheological definitions and nomenclature. *Rheol. Bul.* 12: 6-12.
- (19) CONREY, G. W. 1946 Report of committee on terminology (sect. V). *Soil Sci. Soc. Amer. Proc.* (1945) 10: 479-480.
- (20) CONVERSE, F. J. 1944 Suggested method of test for direct shear in cohesive soils by the box shear method. In *Procedures for Testing Soils*. Amer. Soc. Testing Mater., Philadelphia.
- (21) CULPIN, C. 1936 Studies on the relation between cultivation implements, soil structure and the crop: I. *Jour. Agr. Sci.* 26: 22-35.
- (22) GARDNER, W. 1940 Foundations of soil physics research. *Soil Sci. Soc. Amer. Proc.* (1939) 4: 3-6.
- (23) HÉNIN, S. 1936 Some results obtained in soil investigations by means of the dynamometer borer of Demolon-Hénin. *Soil Res.* 5: 1-20.
- (24) HÉNIN, S. 1937 Signification des resultats obtenus avec les sondes dynamometriques. *Internatl. Soc. Soil Sci. Trans. 6th Comn.* B: 461-467.
- (25) HOUSEL, W. S. 1939 The shearing resistance of soil—its measurement and practical significance. *Amer. Soc. Testing Mater. Proc.* 39: 1084-1099.
- (26) HOUWINK, R. 1937 Elasticity, Plasticity and Structure of Matter. Cambridge University Press, London.
- (27) HVORSLLEV, M. J. 1939 Torsion shear tests and their place in the determination of the shearing resistance of soils. *Amer. Soc. Testing Mater. Proc.* 39: 999-1022.
- (28) KEEN, B. A. 1931 The Physical Properties of the Soil. Longmans Green and Co., New York.
- (29) KEEN, B. A., AND CASHEN, G. H. 1932 Studies in soil cultivation: VI. *Jour. Agr. Sci.* 22: 126-134.
- (30) KRYNINE, D. P. 1941 Soil Mechanics. McGraw-Hill, New York.
- (31) PALMER, L. A. 1944 Suggested method of test for true shearing resistance of soil samples by the direct shear method. In *Procedures for Testing Soils*, pp. 85-86. Amer. Soc. Testing Mater., Philadelphia.
- (32) POKROWSKY, G. I., AND BULYTSHEV, W. G. 1933 Mechanische Eigenschaften disperser Systeme: I. *Kolloid Ztschr.* 64: 175-178.
- (33) POKROWSKY, G. I., NASSEDKIN, N. A., AND SINELSCHIKOV, S. I. 1938 Soil compression at various rates of deformation. *Pedology* 33: 59-69. (Russian with English summary.)
- (34) Public Roads Administration 1942 Classification of soils and procedures used in construction of embankments. *Pub. Roads* 22: 263-282.
- (35) Public Roads Administration 1943 Principles of Highway Construction as Applied to Airports, Flight Strips and Other Landing Areas for Aircraft. U. S. Government Printing Office, Washington, D. C.
- (36) REED, I. F. 1940 Use of power driven soil resistance recorder for study of compaction of soils by tractors. *Agr. Engin.* 21: 281-283.
- (37) RHODES, E. O. 1938 A machine for testing highway subgrade soils. *Amer. Soc. Testing Mater. Proc.* 38 (Pt. II): 551-571.

- (38) RICHARDS, S. J. 1942 A soil penetrometer. *Soil Sci. Soc. Amer. Proc.* (1941) 6: 104-107.
- (39) ROBERTS, R. C. 1930 A suggested method for the determination of the upper plastic limit of soils. *Amer. Soil Survey Assoc. Bul.* 11: 56-60.
- (40) RUSSEL, J. C. 1928 Report of the subcommittee on soil structure and consistency. *Amer. Soil Survey Assoc. Bul.* 9: 10-22.
- (41) RUSSEL, J. C., AND WEHR, F. M. 1928 The Atterberg consistency constants. *Jour. Amer. Soc. Agron.* 20: 354-372.
- (42) RUSSEL, J. C. 1930 Observations on plastic flow in soils. *Amer. Soil Survey Assoc. Bul.* 11: 61-71.
- (43) SCHOFIELD, R. K., AND SCOTT BLAIR, G. W. 1932 Rapid methods of examining soils: I. *Jour. Agr. Sci.* 22: 135-144.
- (44) SCOTT BLAIR, G. W. 1929 The rheology of soil pastes. *Jour. Rheol.* 1: 127-138.
- (45) SCOTT BLAIR, G. W., AND SCHOFIELD, R. K. 1932 The pachimeter as an instrument for testing materials, with special reference to clays, soils and flours. *Jour. Rheol.* 3: 318-325.
- (46) SCOTT BLAIR, G. W. 1937 A new laboratory method for measuring the effects of land amelioration processes. *Internatl. Soc. Soil Sci. Trans. 6th Comn.* B: 417-422.
- (47) SCOTT BLAIR, G. W. 1937 Compressibility curves as a quantitative measure of soil tilth. *Jour. Agr. Sci.* 27: 541-556.
- (48) SCOTT BLAIR, G. W. 1938 An Introduction to Industrial Rheology. Blakiston's Son and Co., Philadelphia.
- (49) SCOTT BLAIR, G. W., AND CASHEN, G. H. 1938 Compressibility curves as a quantitative measure of soil tilth: II. *Jour. Agr. Sci.* 28: 367-378.
- (50) SCOTT BLAIR, G. W. 1944 A Survey of General and Applied Rheology. Pitman Publishing Corporation, New York.
- (51) SHAW, B. T., HAISE, H. R., AND FARNSWORTH, R. B. 1943 Four years' experience with a soil penetrometer. *Soil Sci. Soc. Amer. Proc.* (1942) 7: 48-55.
- (52) SHAW, C. F. 1927 Report of the committee on soil terminology. *Amer. Soil Survey Assoc. Bul.* 8: 85.
- (53) STAUFFER, L. H. 1927 Measurement of physical characteristics of soils. *Soil Sci.* 24: 373-379.
- (54) STONE, A. A., AND WILLIAMS, I. L. 1939 Measurement of soil hardness. *Agr. Engin.* 20: 25-26.
- (55) TEMPLIN, E. H. 1948 Report of committee on terminology relating to soil consistence. *Soil Sci. Soc. Amer. Proc.* (1947) 12: 524-525.
- (56) Tentative Definitions of Terms Relating to Rheological Properties of Matter, A.S.T.M. Des. E 24 - 37 T. 1941 *Rheol. Bul.* 12: 11.
- (57) TERZAGHI, C. 1926 Simplified soil tests for subgrades and their physical significance. *Pub. Roads* 7: 153-162.
- (58) TERZAGHI, C. 1931 The static rigidity of plastic clays. *Jour. Rheol.* 2: 253-263.
- (59) UNGAR, G. 1934 Plastometrische Untersuchungen an hochkonsistenten Substanzen: I. *Kolloid Ztschr.* 69: 30-35.
- (60) United States Department of Agriculture 1938 Soils and Men, *Yearbook* 1938: 1165.
- (61) VASSILENKO, P., AND SETZINSKY, A. 1933 Resistance of soils to compression as one of the factors determining the work of agricultural implements. *Pedology* 28: 443-463. (Russian with English summary.)
- (62) VEIHMEYER, F. J. 1929 An improved soil sampling tube. *Soil Sci.* 27: 147-152.
- (63) WARD, A. G. 1948 The rheology of stiff pastes. *Phys. in Indus.* 25: 387-396.

MINERALOGICAL ANALYSIS OF SOILS

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As a result of development of techniques and equipment especially adapted to study of soils and other finely divided sediments, mineralogical analysis of soils is receiving more and more attention as a part of soil science. The importance of mineralogical studies of soil has never been seriously questioned, but procedures have been lacking by means of which information could be accumulated rapidly and applied to large areas. Such information is desirable for classifying soils, for determining their mode of formation, and for interpreting certain aspects of fertility studies as well as basic chemical and physical properties.

It must be remembered that a relatively few mineral families comprise the bulk of the soil. These consist of feldspar, quartz, mica, clay minerals, and in the lateritic soils the oxides and hydroxides of iron and aluminum. It is, of course, possible and often useful to identify a very large number of individual mineral species, particularly among the accessory minerals the percentage content of which is low. Nevertheless, knowledge of the distribution of the gross mineral components permits a description of the principal mineralogical characteristics of soils.

Mineralogical studies of soils can therefore be considered from two general viewpoints:

1. Determination of the principal constituent minerals, their nature and characteristics.
2. Determination and study of the accessory minerals and their relationships.

In addition to techniques for determining the various mineral components of soils, improved techniques have recently been developed for studying thin sections of undisturbed soil to determine the manner in which minerals occur in soils. This phase of soil mineralogical study has not been explored fully because of difficulties in embedding materials. The work of Bourbeau and Berger (2) with methyl methacrylate ("Castolite") type plastic shows that these difficulties can be overcome and results of definite interest to the pedologist can be obtained.

EQUIPMENT AND APPARATUS

Regardless of the type of mineralogical soil investigation, certain items of equipment are necessary. These are as follows:

Petrographic microscope of good standard design.

Immersion oils, a set carefully calibrated.

Refractometer, preferably an Abbe.

Vacuum pump and accessories.

Heavy liquids for mineral separations, usually *s*-tetrabrom ethane and nitrobenzene.

Centrifuge and tubes for mechanical and heavy liquid separations, usually International No. 2 with head No. 240.

¹ Joint contribution. This work was supported in part by the Wisconsin Alumni Research Foundation.

Supercentrifuge for fractionating the finer clay separates, usually the Sharples air-driven type with clarifier type bowl.

X-ray spectrometers, especially adapted for fine-grained materials, Geiger counter, and film types.

The petrographic microscope

The petrographic microscope is used for determining optical characteristics of crystalline materials in sediments and thin sections. The principal optical characteristics determined to identify a compound are: 1. Refractive indexes and optic sign, 2. Pleochroism, 3. Extinction angles. Determination of these optical characteristics and comparison with known data will generally be ample to determine the mineral under consideration.

Immersion oils²

The principal refractive indexes of minerals is determined by immersing the mineral in a series of oils of known index and observing by the method of central or oblique illumination when the index of the oil and the mineral for critical directions in the crystal is the same. Suitable oils have been described by Emmons (5), Larsen (16), and others. The list recommended by Emmons with their indexes at 24°C. (table 1) is adequate for most minerals encountered in soils.

The refractometer

The refractive indexes of the oils used in immersion work must of necessity be checked at intervals to be sure that no changes in composition have occurred. The Abbe type refractometer is ideal for the liquids listed in table 1. For liquids with an index higher than N_D 1.74 the Fisher Co. of Pittsburgh offers a refractometer which, with suitable filters, can be read up to N_D 1.90. The accuracy of this instrument is about 0.005, which is close enough for oils of such a high index.

Heavy liquids

Many heavy liquids have been suggested for separating minerals; the most satisfactory for soil mineral studies consist of mixtures of *s*-tetrabromethane and nitrobenzene as described by Volk (27). The maximum density for *s*-tetrabromethane is about 2.95, and dilution with nitrobenzene (density about 1.20) gives a series of liquids appropriate for separating the important mineral constituents of soils. The similarity in boiling points makes these liquids especially desirable for liquid mixtures of different specific gravities, because in routine separations, mixtures of minerals and liquids are evacuated to remove air bubbles which inhibit good separations, and because of the similarity in boiling points the specific gravity of the liquid remains unchanged after evacuation. The density of liquids should always be tested either by a pyc-

² Where preparation is not feasible, sets of oils with standardization may be procured from R. P. Cargille, 118 Liberty Street, New York 6, N. Y., or J. T. Rooney, Box 853, Buffalo, N. Y.

nometer or hydrometer, although Volk has worked out a procedure which utilizes the variation of the refractive index of the aforementioned liquid mixtures with their specific gravities and which is rapid, accurate, and convenient for use where only small volumes of liquid are available.

TABLE 1
Liquids suitable for immersion media (5)

LIQUID	$N_D^{24^\circ\text{C.}}$	TEMPER- ATURE COEFFICIENT	DARK CONTAINER
Trimethylene chloride....	1.446	.00045	
Cineol	1.456	.00041	
Hexahydrophenol.....	1.466	.00044	
Decahydronaphthalene ..	1.477	.00040	
Isoamylphthalate	1.486	.00038	
Tetrachloroethane....	1.492	.00051	
Pentachloroethane.....	1.501	.00048	
Trimethylene bromide ..	1.513	.00048	
Chlorobenzene	1.523	.00053	
Ethylene bromide + chlorobenzene ..	1.533	.00054	
O-Nitroluene.	1.544	.00053	
Xylidine ..	1.557	.00050	X
O-Toluidine ..	1.570	.00047	X
Aniline.	1.584	.00045	X
Bromoform ..	1.595	.00056	
Idobenzene + bromobenzene ..	1.603	.00054	X
Idobenzene + bromobenzene.....	1.613	.00054	X
Quinolin	1.622	.00049	X
α -Chloronaphthalene.....	1.633	.00044	
α -Bromonaphthalene + α -Chloronaphthalene.....	1.640	.00044	
α -Bromonaphthalene + α -Chloronaphthalene.....	1.650	.00044	
α -Bromonaphthalene + α -Iodonaphthalene.....	1.660	.00045	X
α -Bromonaphthalene + α -Iodonaphthalene.....	1.670	.00044	X
α -Bromonaphthalene + α -Iodonaphthalene.....	1.680	.00044	X
α -Bromonaphthalene + α -Iodonaphthalene...	1.690	.00044	X
Methylene iodide + iodobenzene.....	1.700	.00060	X
Methylene iodide + iodobenzene.....	1.710	.00063	X
Methylene iodide + iodobenzene.....	1.720	.00066	X
Methylene iodide + iodobenzene.....	1.730	.00068	X
Methvlene iodide.....	1.738	.00070	X

Centrifuge tubes for heavy liquid separations

Various tubes have been devised for separating minerals in groups according to their specific gravities. Marshall and Jeffries (20) have described four types that are particularly adapted to soils (fig. 1).

Heavy liquid separations in general should be carried out by centrifuging mixtures of minerals and heavy liquid only after evacuating the mixture to remove occluded air, and all separations should be checked for completeness by means of the microscope.

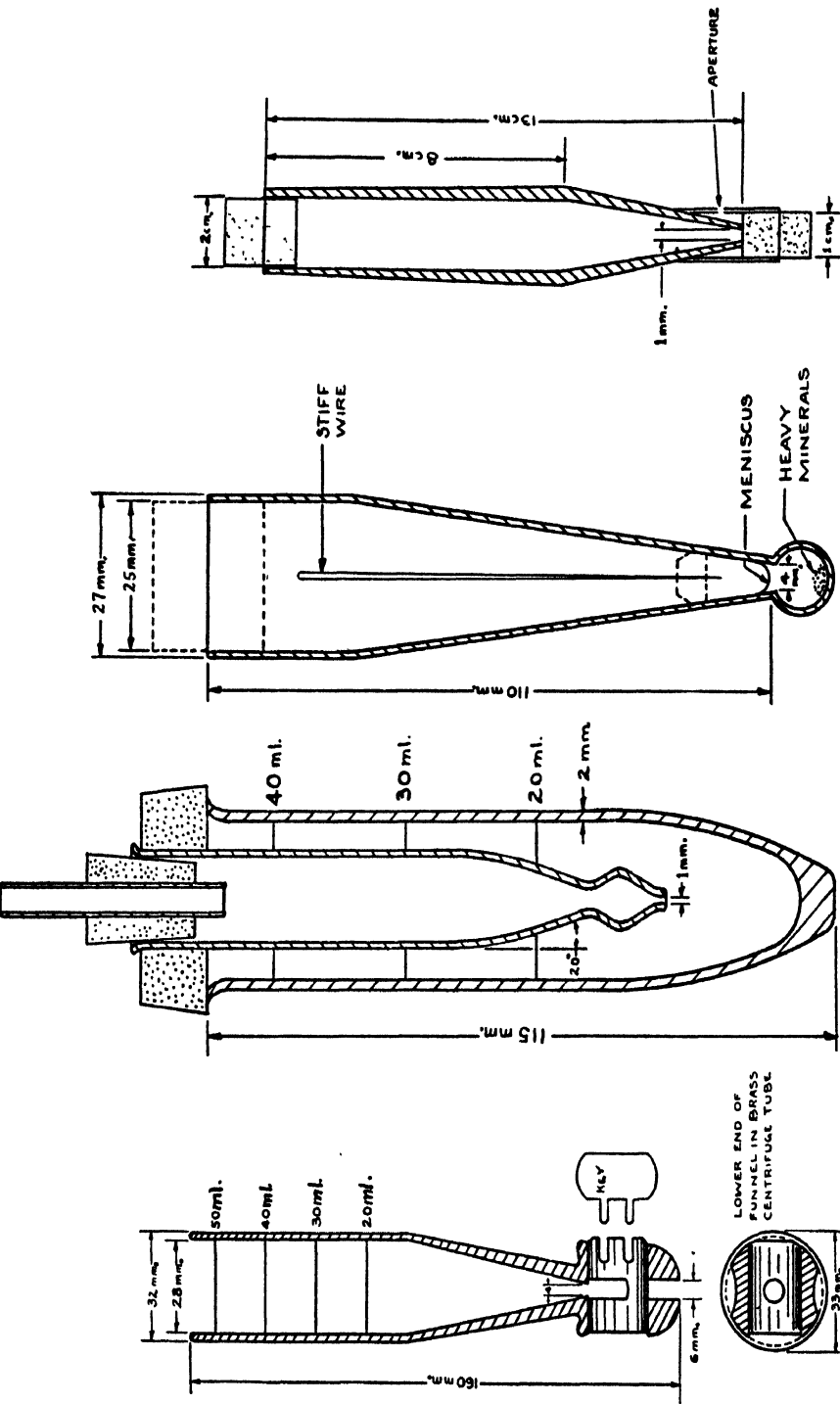


FIG. 1. CENTRIFUGE TUBES ADAPTED TO HEAVY LIQUID SEPARATIONS OF SOIL MINERALS (20)

Identification

Detailed methods for optical identification of the various minerals common in soils would be out of place here. As a rule, determination of the refractive indexes, optic sign, pleochroism, and extinction angles is sufficient to identify a mineral. After these properties have been determined, reference to standard works listing characteristics is necessary to complete the identification.³ In addition, sets of known minerals permanently mounted are useful references.

These properties and references supply adequate theoretical and descriptive information for microscopic identification of crystalline compounds and of virtually all the common minerals found in the sand and silt fraction of soils. Knowledge of the theory and continual practice are essential for optical identification of crystalline materials. This cannot be overemphasized.

If additional information other than the gross mineral composition of the soil is desired, the accessory or heavy mineral groups may be studied. The course of weathering and relationships to parent material (16) may frequently be discovered by study of the accessory minerals.

X-ray spectrometers

In the x-ray spectrometer method for studying single crystals, the movement of a Geiger counter or electrometer is synchronized to pick up the diffracted beam as the crystal is rotated about each optic axis. This method is laborious because the crystal must be oriented carefully on each optic axis and the diffraction maxima recorded one at a time. A great stride forward was made by adapting a photographic film to the x-ray spectrometer to record automatically the many diffraction maxima as the crystal was rotated. In the powder x-ray spectrometer, developed by Hull and by Debye and Scherrer, fine grain crystals were mounted in place of the single crystal and the diffraction maxima for all orientations of the crystals recorded simultaneously on the film. This method made x-ray diffraction analysis relatively rapid, and several efficient types of equipment became commercially available. Tumbling of the sample recently has been adapted to handling soil particles of fine sand and silt sizes as powders.

The Geiger counter has recently been very successfully adapted (3, 4, 5) to the powder type x-ray spectrometer. This step has combined the rapidity of the powder technique with the rapid recording of individual diffraction maxima by the Geiger counter, previously available only for single crystals. Development of a focusing feature in the design (3, 4) greatly increases the intensity of the diffracted beams. Also, this feature permits the use of a rather broad area of sample, which has the same effect as tumbling a coarser-grained powder sample, and permits the recording of a powder pattern for sand and silt fractions.

Because of the common occurrence of iron compounds as characteristic com-

³ The following reference books are an essential part of the laboratory library:

Larsen and Berman (16).

Milner, H. B. Sedimentary Petrography, ed. 3. Thos. Murby & Co., New York. 1940.

Krumbein, W. C., and Pettijohn, F. J. Manual of Sedimentary Petrography. D. Appleton-Century Co., New York. 1938.

ponents of the colloid fraction, an iron-target x-ray tube is used in the film type x-ray spectrometer and is considered the most satisfactory for x-ray diffraction of soil colloids. A shortened exposure time is an advantage gained by use of unfiltered K x-radiation. For soil clays the positions of the K^B diffraction lines are known in relation to the positions of the Ka lines in the various standard minerals, and thus do not interfere. A copper-target x-ray tube, employed in the Geiger counter x-ray spectrometer, is suitable for samples in which the iron content is low, for example in most silt and sand fractions. Since the copper-target intensity is considerably greater, a filter (nickel foil) may be employed to remove the K_B ray without too great sacrifice in exposure time.

Most early x-ray diffraction studies related to soils were confined to the clay fraction, but the development of these improved techniques is resulting in studies of the silt and sands as well. Successful studies (15) have been carried out on the essential mineral composition of soils and on transportation and deposition in soils. The speed with which data are obtained is an outstanding advantage in this type of work.

PREPARATION OF SOILS FOR MINERALOGICAL ANALYSIS

The success of mineralogical analyses of soils depends to a great degree on the manner in which the sample is treated prior to analysis. A factor which formerly hindered detailed petrographic study of soils was the presence of free iron oxides as a coating on the surface of particles. Iron oxide also serves in some cases as a cement, resulting in aggregates of particles which hinder mechanical heavy liquid separations. Soil organic matter also acts as a cementing agent and coating on soil particles and thereby hinders separation and identification.

Removal of organic matter

To 10 gm. of air-dried screened soil in a 600-ml. beaker, add 10 ml. of 30 per cent H_2O_2 , cover with a watch glass, and let stand overnight at room temperature. Place on a hot plate maintained at a temperature of 60° to 75°C. until effervescence ceases, remove cover glass, washing back any soil that has spattered on it and the sides of the beaker, and evaporate nearly to dryness. Two such treatments generally remove most of the organic matter (25).⁴ If the soil is alkaline or calcareous, effervescence may be violent; this can be reduced by adding N HCl to give a slightly acid reaction which persists. Soils thus treated are ready for removal of the free oxides.⁴

Removal of free iron oxides

It has been found that the free iron oxides can be removed from soils by reduction with either nascent hydrogen or nascent hydrogen sulfide. In the reduction by nascent hydrogen sulfide, a residue of free sulfur is formed as well as ferrous oxalate, both of which

⁴ The cation-exchange capacity of many soils is decreased 25 to 50 per cent by these methods. This decrease may be taken to mean that a considerable portion of the clay is destroyed by the treatment. However, by preparing a separate soil sample with caution not to dry the sample during the H_2O_2 treatment and omitting the iron oxide removal treatments, the inorganic colloid fraction can be separated and x-rayed to determine the complete clay and the crystalline iron oxides as well. The cleaned sample is used for the petrographic analyses and x-ray determinations of the sand and silt and the resistant portion of the clay.

must be removed before mechanical analysis. Methods utilizing nascent hydrogen do not present these difficulties.

Nascent hydrogen method (14). Place 2 gm. of 20-mesh soil into a weighed 100-ml. Pyrex centrifuge tube, add 10 ml. 0.1 *N* HCl, allow to stand for 1 hour, and wash three times with 5 per cent NaCl. Add 5 ml. of 10 per cent H_2O_2 , stir thoroughly, let stand 2 hours at room temperature, then place on a steam bath and evaporate to dryness. Repeat until virtually all organic matter is decomposed. Usually two treatments are ample. Add 40 ml. of solution containing 4.15 gm. potassium oxalate, stir thoroughly until all dried organic-matter-free soil is loosened from the bottom of the tube, place the tube in a boiling water bath, and heat to about 80°C., add 10 ml. of solution containing 0.95 gm. of oxalic acid, stir, and heat to 90°C. Place a strip of magnesium ribbon about 8 inches long and weighing about 0.2 gm. in the hot suspension, stir, and maintain temperature at 90° to 95° for 3 to 5 minutes. Remove magnesium ribbon, add 5 ml. of solution containing 0.48 gm. oxalic acid, and continue heating 3 minutes or until clays and sands are white or gray. Centrifuge at once, and wash free of iron with 50-ml. portions of 5 per cent NaCl solution. Usually four washings are sufficient. After free of iron, wash twice with 20 ml. of 95 per cent alcohol and twice with 20 ml. of acetone. Allow the excess of acetone to evaporate on the hot plate, place in an oven at 100°C. for 5 hours, cool, and weigh iron-oxide-free soil.

Nascent hydrogen sulfide method (25). Place 10 gm. of ordinary soil (5 gm. of a lateritic soil) pretreated with H_2O_2 in a liter beaker. Add 650 ml. of water and 5 ml. of 20 per cent solution of $Na_2S \cdot 9H_2O$ and boil for 5 minutes. Add 10 gm. of ammonium chloride. By means of steam or other convenient source of heat, keep the suspension at a temperature of 80° to 90°C. until it is ready for centrifuging. Do not heat to boiling during this time. In the procedure that follows, one should work expeditiously, except in passing from pH 7 to pH 6, the stage in which the H_2S is liberated. This stage should take a minute or two each time, to get efficient and effective action of the nascent H_2S being liberated. Immediately add oxalic acid in small amounts at a time (either finely powdered crystals or solution may be used) with vigorous stirring until pH 6 is reached; use bromthymol blue indicator on a spot plate. Add 10 ml. more of the 20 per cent solution of $Na_2S \cdot 9H_2O$, stir, and then add oxalic acid rapidly until pH 7 is again reached. Again reduce the pH slowly from 7 to 6, and then rapidly to pH 3.5, using bromphenol blue indicator on a spot plate. Stir and let stand for a few minutes till black sulfides have dissolved. Bring the pH back to 7 with 2 *N* NH_4OH , forming FeS and $(NH_4)_2S$ with the H_2S in solution, and then add 2 *N* HCl drop by drop with vigorous stirring until a pH of 6 is again reached, liberating nascent H_2S again from the $(NH_4)_2S$, and then more rapidly until pH 3.5 is reached, using bromphenol blue indicator on a spot plate. After digesting for a minute or two, the suspension should assume a light gray color free of any yellowish or reddish tinge of iron oxide, unless a lateritic soil is being treated.

For a lateritic soil (one containing 10 per cent or more of free iron oxides), use a 5-gm. sample, and bring the solution back to pH 7 with NH_4OH twice more than the regular directions call for, adding 1 additional gram of $Na_2S \cdot 9H_2O$ each time after pH 7 is reached, and use oxalic acid throughout in bringing the solution down to pH 3.5.

In either case, digest at 80° to 90°C. until coagulation takes place, but no longer. Transfer to centrifuge tubes, let stand a few minutes in a hot water bath, and then centrifuge immediately, using four centrifuge tubes, and wash twice with 0.001 *N* HCl containing 5 per cent NaCl. Pour all the supernatant liquid into a beaker so it may be analyzed later for iron, aluminum, and silicon.

At this stage, examine the soil in the tubes, and if there is some ferrous oxalate present, indicated by a greenish yellow ring or patch, add 10 ml. of 0.001 *N* oxalic acid and 2.5 ml. of 10 per cent H_2O_2 to each tube, and shake. Let stand for about 10 minutes, or until reaction ceases, and then bring to pH 2 with 10 per cent oxalic acid, stirring vigorously and using thymol blue indicator on a spot plate. After about 5 minutes, when decomposition and solution are complete, add 50 ml. of *N* NaCl solution to each tube, shake, and after coagulation, centrifuge and wash twice with 0.001 *N* HCl containing 5 per cent NaCl, and then

once with 5 per cent NaCl to reduce the acidity in the residue. Pour supernatant liquid into the beaker containing the main portion of the solution of free iron and aluminum oxides.

To remove the sulfur that contaminates the soil, wash twice with 95 per cent ethyl alcohol saturated with NaCl to remove water, and then three times with carbon disulfide solution (1 volume CS_2 to 2 volumes 95 per cent $\text{C}_2\text{H}_5\text{OH}$ saturated with NaCl), and finally four to five times with 95 per cent ethyl alcohol saturated with NaCl to remove CS_2 . The soil is now ready for mechanical analysis.

Mechanical analysis

The mineral character of soils is reflected principally in the very fine sand (0.10–0.05 mm.), silt (0.05–0.002 mm.), and clay fractions (0.002 mm.). For x-ray diffraction analysis of the inorganic colloids the clay fraction is further separated into fractions 2 to 0.2 μ (26), 0.2 to 0.08 μ (22), and 0.08 μ . The following procedure is applicable (10) either with or without prior treatment for removal of iron oxides.

After saturating the iron-oxide-free soil with sodium by washing four times with 5 per cent NaCl, transfer to a liter beaker with 500 to 600 ml. of water. Stir thoroughly and, with the beaker not more than two-thirds full, allow at least 10 minutes for settling. Then decant the suspension as far as conveniently possible, being careful not to decant any of the sand. Wash the sand and remaining silt and clay from the beaker onto a 300-mesh sieve which is supported on a glass funnel, wash the silt and clay through the sieve by means of a jet of water, and collect it in a beaker containing the decanted portion. Wash the sand twice with alcohol and twice with acetone, dry a few minutes, and tap the sieve over the same funnel to pass the remaining silt and clay. Dry sands at 105° to 110°C., and weigh.

Transfer the thoroughly agitated suspension of silt and clay to 100-ml. centrifuge tubes, filling exactly to the 10-cm. mark, allow to stand overnight or at least 8 hours per 10-cm. suspension depth, and decant the clay (<0.002 mm.) carefully into a 6-liter florence flask, being careful not to disturb any of the sediment. Wash the sedimented silt into two centrifuge tubes and run at 1,000 revolutions per minute for 3 minutes (24, 25, 26). Carefully decant the supernatant suspension into the 6-liter flask and add wash solution exactly to the 10-cm. mark. The wash solution consists of water containing just enough Na_2CO_3 to give it a pH 9.0. Stopper and shake tubes vigorously until all the material in suspension is well dispersed. Centrifuge, decant, add water, and shake exactly as before, only shorten time of centrifuging to 2 minutes. Repeat until the supernatant liquid after centrifuging appears fairly clear. Usually 10 washings are sufficient. Wash the silt into a beaker with alcohol, evaporate, dry, and weigh.

Dilute the suspension to a definite volume, flocculate an aliquot with N HCl, wash four times with methanol, and transfer to a weighed crucible with water. Evaporate, dry at 105°, cool, and weigh and compute the total clay.

Flocculate the clay in the flask by adding 20 to 60 gm. of NaCl and digesting on the hot plate. Siphon off supernatant liquid, and complete separation by means of the centrifuge.

The 2- μ clay fraction may be studied directly for general information. Because of particle-size effects on diffraction intensities and other factors (22, 26) discussed later, however, accurate interpretation of the mineralogy of the inorganic colloid fraction of soils requires separation of the minerals at 0.2- and 0.08- μ limits. To accomplish this, run the dispersed 2- μ fraction through a Sharples supercentrifuge (clarifier type bowl, R_1 = 0.87 inch and R_2 = 0.29 inch with 0.005-inch cellulose acetate liner) at 470 ml. per minute and 30,000 revolutions per minute for the 0.2- μ limit and 200-ml. per minute at 50,000 revolutions per minute for the 0.08- μ limit. Three to five repeated separations at the 0.2- μ limit and three at the 0.08- μ limit are ample.

HEAVY LIQUID SEPARATIONS

Soil mineral studies in general consist of the study of relatively few mineral groups, that is, quartz, feldspar, muscovite, accessory or heavy minerals, and

the clay group. Since the clay groups are ordinarily isolated by sedimentation technics, heavy liquid separations are generally confined to the sand and silt fractions. This necessitates separation of these fractions into four groups. In routine procedure it is useful to separate these in the following order:

1. Heavy mineral or accessory group..... sp. gr. 2.957
2. Muscovite group..... sp. gr. 2.72-2.80
3. Quartz group..... sp. gr. 2.65
4. Feldspar group..... sp. gr. 2.55-2.76

It will be noted that in some cases these fractions overlap in specific gravity; hence, careful microscopic study for completeness of separation is necessary in all instances. A petrographic analysis of these groups is ample to establish the mineral character of the sands and silt fractions. Study of groups 2, 3, and 4 gives information concerning the gross mineral composition of soils.

X-RAY DIFFRACTION ANALYSIS OF SOIL MINERALS

In practice, diffraction patterns of the soil fractions being studied are compared with patterns of known minerals, to establish their mineral composition. The details of a mineral analysis of soils by this procedure are as follows:

1. Removal of iron oxides (omitted for certain types of studies of the inorganic colloids).
2. Mechanical separations.
3. Preparation of the diffraction patterns, by (a) the film technic, (b) Geiger count x-ray spectrometer.
4. Identification by comparison with standard diffraction patterns.
5. Quantitative estimation of amounts from diffraction intensities at characteristic angles.

X-RAY DIFFRACTION ANALYSIS OF CLAYS

In the preparation of clays for x-ray diffraction analysis, it is assumed that some of the montmorillonite series (expanding lattice) of clay minerals might occur in the sample. The preparation procedure is so designed that this type of mineral, if present, is solvated sufficiently to be detected by the x-ray diffraction method. The diffraction of x-rays by the basal (001) planes of this series of minerals is highly variable in intensity according to procedure of preparation. The chief sources of variation center around the degree of uniformity in spacing of the crystal plates, which varies (1, 9, 12) with the type of cation saturation, the degree of solvation, and the physical stresses set up in the crystal during drying. Diffraction procedures have been worked out employing saturation of the clay with large organic cations (8, 11) and employing calcium saturation (12). Calcium saturation of the clays, combined with appropriate solvation, tends to give a greater (001) line intensity of the montmorillonite species common in soils than other cation saturations, organic or inorganic (12). Procedures for solvation with water (1, 9) or with glycerol (17, 18, 28),⁵ with clays in sus-

⁵ White, J. D., Pennington, R. P., and Jackson, M. L. Glycerol solvation of montmorillonite and hydrous clay-intermediates for x-ray diffraction analysis. Manuscript, University of Wisconsin, Madison. 1949.

pension in the nonpolar liquid, benzene, have been developed. The procedures (1, 28) involving benzene as a medium from which the clay is dried increase the (001) diffraction intensity of montmorillonite powder samples greatly over that obtained by drying from water alone, or from water in the presence of a few drops of glycerol (17). The procedure for glycerol solvation in benzene has some advantages of convenience and rapidity over the procedure for controlled hydration in benzene (1) and thus is more suitable for routine use. The controlled hydration procedure, however, gives more satisfactory results with some montmorillonitic soil clays.

Preparation of sample

The clay sample for analysis has generally been separated by dispersion in an alkaline medium. The clay suspension so obtained is thoroughly shaken and an aliquot containing an amount of clay estimated to weigh 100 mgm. is removed volumetrically with a pipette and placed in a 100-ml. centrifuge tube. The clay is flocculated with a few drops of 0.5 *N* HCl (bringing the suspension to pH 3 or 3.5), washed with three portions of ethanol of pH 3 to 3.5, and transferred to a weighed platinum crucible with water. The clay is oven-dried at 105°C. and weighed. (This sample is analyzed for total potassium.) The percentage of each clay fraction of the soil is calculated from this weight. Also, on the basis of this weight, a 50-mgm. subsample is taken from the original suspension by means of a Mohr pipette and prepared for x-ray diffraction analysis.

Calcium-saturation of clay. The 50-mgm. clay sample taken for x-ray diffraction analysis is transferred to a 125-ml. Erlenmeyer flask containing 25 ml. of 0.3 *N* NaAc solution the pH of which has been adjusted to 3.5 with HCl. This suspension is mixed, heated to boiling for 5 minutes, flocculated with 2 ml. of 10 *N* CaCl₂ solution, transferred to a 100-ml. centrifuge tube, clarified by centrifuging, and the supernatant solution decanted. The clay sample is then washed five times with calcium solutions (first, fourth, and fifth with 0.5 *N* CaCl₂ solution of pH 7; the second and third with *N* CaAc₂ solution of pH 7.7) to remove exchangeable hydrogen. It is next washed with methanol until free of chlorides; this usually requires four or five washings, with stepwise increase in methanol concentration from 60 per cent in the first washing to absolute methanol in the last two. The sample is washed three times with a benzene ethanol solution (10:1 by volume solution of benzene and anhydrous ethanol).

Glycerol solvation of clay. To the 50-mgm. sample in the bottom of the centrifuge tube, from which the benzene-ethanol solution has been decanted, are added about 50 ml. of a ternary solution consisting, by volume, of 0.4 per cent glycerol, 9 per cent ethanol, and the remainder benzene (1.80 ml. of anhydrous glycerol dried over P₂O₅ is dissolved in 40 ml. of absolute ethanol, and 400 ml. of benzene added). The tube is stoppered and shaken, the stopper and walls are washed down with more of the ternary mixture, and the suspension is allowed to stand 30 minutes for sorption of the glycerol monolayer.

Washing with benzene. Next the clay is thrown from suspension by centrifuging and the supernatant liquid decanted slowly but completely. Then exactly 35 ml. of a 200:1 (by volume) benzene-ethanol solution is added, the tube stoppered, and the clay thoroughly suspended.⁶ The clay is washed from the stopper and the tube walls with benzene, thrown down by centrifuging, and then given one additional washing with benzene. About 20 ml. of benzene is then added and the tube agitated by tapping with the fingers to suspend the clay. The sides of the tube are washed down with a small amount of benzene, and the clay is allowed to settle. The excess benzene is decanted, and the suspension is poured into a watchglass of 13 cm. diameter. The watchglass is rotated to distribute the sample in a

⁶ This gives a solution of the glycerol in the residual supernatant liquid [from data of R. P. Pennington and the junior author (1948)].

thin, even layer around the upper periphery of the glass. The excess liquid in the center is removed by imbibition, the corner of a folded filter paper being used as a blotter. The watchglass is placed in a vacuum desiccator containing concentrated sulfuric acid, and full vacuum applied with a water aspirator pump. The air-inlet valve is then opened slightly, to allow slow ventilation with air that has been dried by passing through concentrated sulfuric acid. Evaporation of the benzene is completed in 15 to 20 minutes. The clay is next removed with a spatula and placed in a small vial, stoppered to prevent sorption of water vapor by the glycerol. The sample is now ready for mounting for the x-ray diffraction powder technique.

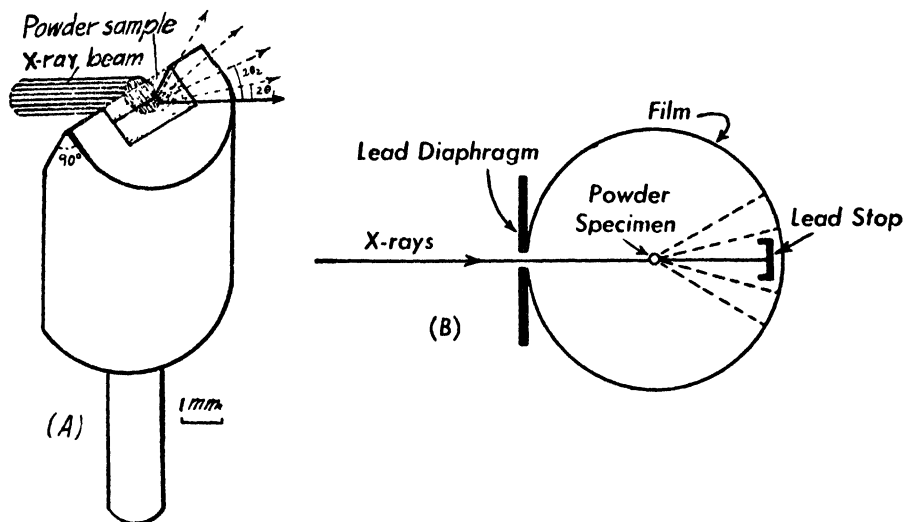


FIG. 2. (A) SECTOR-MOUNTED CLAY POWDER SAMPLE, SHOWING RELATION TO X-RAY BEAM AND DIFFRACTION ANGLES. (B) GENERAL GEOMETRY OF FILM TYPE X-RAY SPECTROMETER

Part (b), from page 43 of *Radiography of Materials*, Eastman Kodak Company, X-ray Division, Rochester, N. Y. 1944.

(Jeffries and Jackson. *Soil Science*: "Mineralogical Analysis of Soils" 1949)

X-ray diffraction of the sample

The clay sample to be x-rayed is formed into a 90° sector-mount by means of two glass slides, a portion of the sample being placed on one slide and, with the edge of a second slide, gently formed into a triangular prism (fig. 2) in the recess of the sector-mount. Care is taken to avoid crystal distortions, which result if the granules of clay are pressed firmly (12). The edge of the wedge is elevated into the x-ray beam until it cuts two thirds to three fourths of the beam. The x-ray cylindrical camera is closed with side plates. Air, dried by passage through sulfuric acid, is circulated about the sample to prevent adsorption of water by the clay while it is being x-rayed. An exact portion to be mounted may be weighed for quantitative work (10).

The sector-type mounting of the powder sample has the advantages that (a) no container is used through which the incident x-ray beam and the relatively weak diffracted x-radiation must pass; (b) a relatively uniform thickness of sample is obtained automatically by the geometry of the mount (fig. 2a);

(c) a unique solution is automatically obtained to the x-ray diffraction and adsorption functions of the beam so as to give maximum diffraction intensity for minerals of varying adsorption characteristics (adsorption increases exponentially with sample thickness, whereas diffraction increases only linearly; a wedge-shaped sample gives a maximum resultant intensity).

Other methods of mounting the powder sample are (a, packing powder in a capillary of plastic or glass; (b) packing powder between thin foils spaced by a punched card of suitable thickness (23); (c) forming the powder into a thin film in a punched metal disc to be mounted in front of the collimator; (d) forming a powder film over the surface of an adhesive on a glass slide, for the Geiger counter spectrometer (7).

In addition to these powder techniques, the layer lattice type silicate colloids are sometimes formed into films in which the crystal plates are oriented in parallel: (a) by drying clay as a film on a glass slide in the presence of glycerol (17), most suited for the Geiger counter spectrometer; (b) by drying on a glass slide from water and shaving off oriented films for mounting parallel to the x-ray beam on a glass thread (21); (c) drying on a glass rod and advancing the curved surface into the beam for diffraction (18). The variability in orientation is sufficient to give the various orders of the basal reflections (to this extent like a powder sample), or the films can be rotated as a "single crystal" to diffract the basal spacings. The (*hk*0) and (*hkl*) reflections are weak or missing (18, 21) and therefore the important (110) (4.45 Å.) line of clays is not available to represent the quantity of mica-intermediates present, which are not well represented by (001) reflections (13, 19, 29).

Eastman Kodak "No-Screen" diffraction film is satisfactory for registration of the pattern. The film is processed in freshly mixed developer for a standardized length of time sufficient to produce maximum contrast. Constant temperature is maintained (10) at $19 \pm 0.1^\circ\text{C}$. in the water bath. The film is developed in a 1-liter cylinder into which the films are suspended from a gently moving agitator.

Interpretation of diffraction pattern

The primary step in interpretation of the x-ray diffraction pattern is measurement of diffraction intensity at characteristic angles. Crystal lattice characteristics of each mineral series determine the intensities and angles of its diffraction maxima. Quantitative interpretation of the percentage composition represented in diffraction patterns is begun with an appraisal of the diffraction intensity of the standard mineral and that of the same component in the test sample, computed relatively, as a ratio or percentage (29). In practice, this relative intensity ratio is measured generally by one of three methods, the first two of which are applicable to film techniques:

1. Visual comparisons of a given diffraction line in the film of the test sample to the corresponding line in a series of diffraction patterns of standard minerals with varying proportions of the expected components (9, 29).

2. Photometric densitometer measurements of the corrected line density D_l on photographic films of the standard and test samples (10).

3. Height of the diffraction maxima measured by the Geiger counter spectrometer, consisting of an ionization chamber oriented at the Bragg angle of the standard and test samples (7).

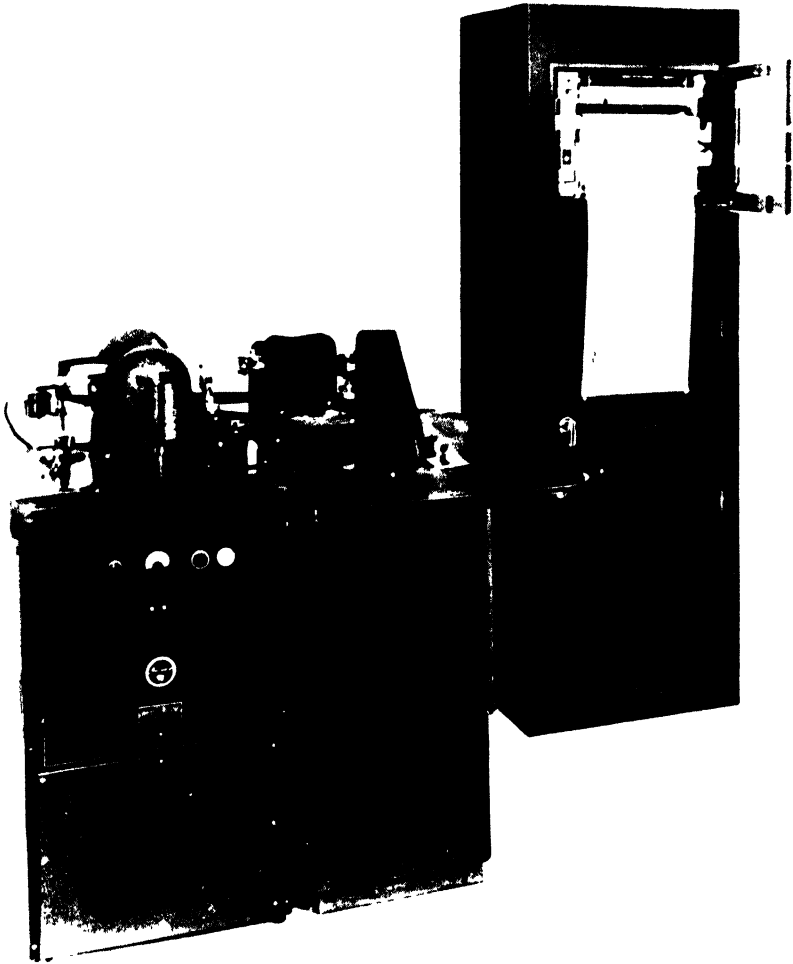


FIG. 3. GEIGER COUNTER X RAY SPECTROMETER
Courtesy of North American Philips Co., New York

Application of all these methods is hampered by as yet incomplete control of a number of variables peculiar to diffraction by clays: (a) variation of lattice perfection or distortion, and crystal habit, changes the relative intensities of the characteristic diffraction maxima, (b) occurrence of amorphous components in clays, by dilution of the sample and by scattering, decreases the intensity of the diffraction maxima recorded for the crystalline soil minerals (22); (c)

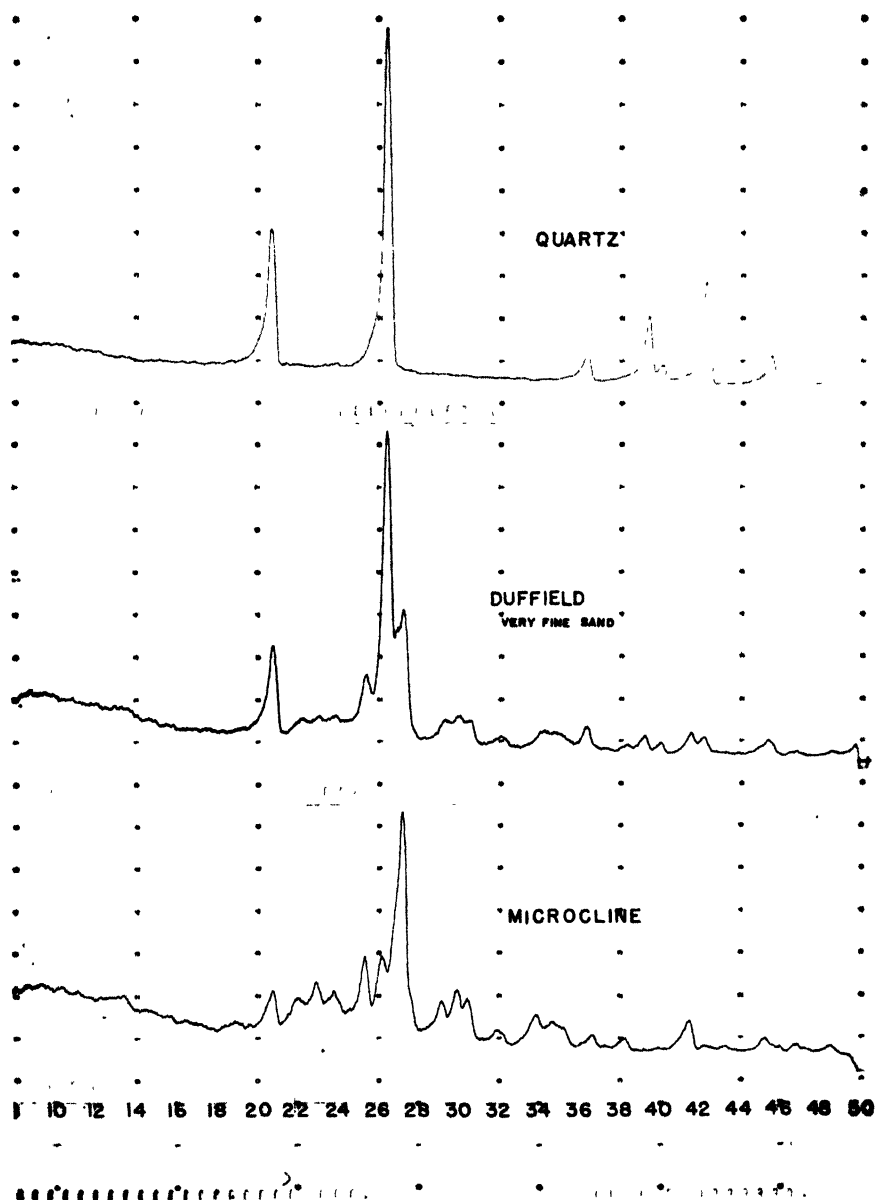


FIG. 4 COMPARISON OF A DIFFRACTION PATTERN OF A VERY FINE SAND SOIL FRACTION WITH STANDARD PATTERNS OF QUARTZ AND MICROCLINE

Figures at bottom indicate angular readings (18) on the goniometer.

diffraction intensity varies with different crystal sizes within the mineral fraction, in general decreasing with particle size; (d) the basal reflections of mica-intermediates are weak or missing (4, 13, 19, 22, 29), requiring indirect interpretations, from the (110) (4.45 Å.) diffraction line intensity which coincides

with lines from the montmorillonite and kaolinite series; and (e) the diffraction intensity of the montmorillonite series is extremely variable according to

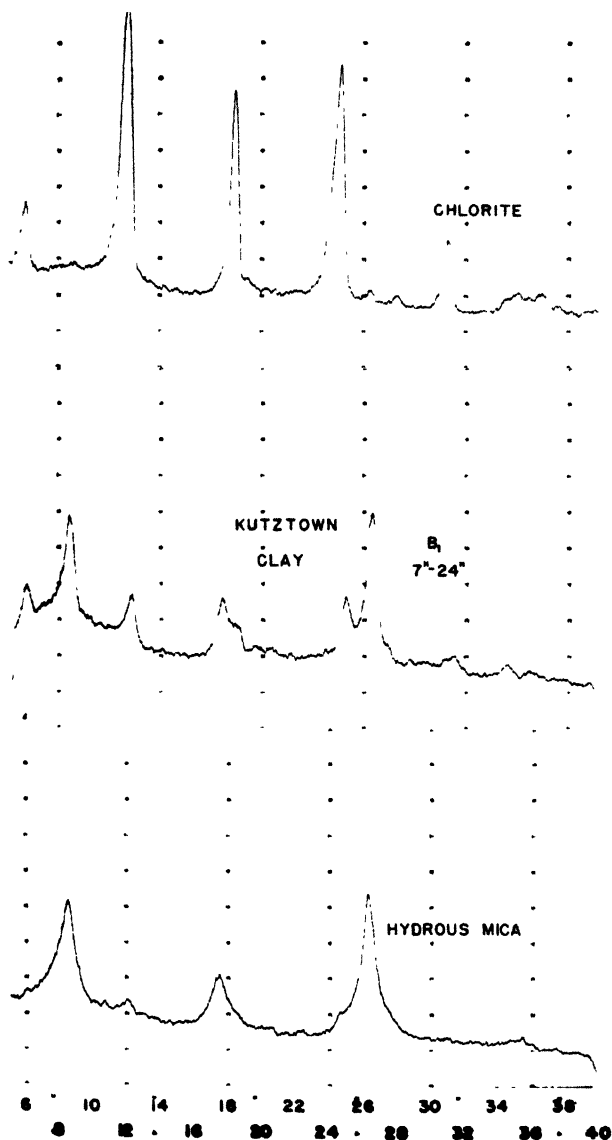


FIG. 5. COMPARISON OF A DIFFRACTION PATTERN OF A SOIL CLAY WITH STANDARD PATTERNS OF HYDROUS MICA AND CHLORITE

Figures at bottom indicate angular readings (18) on the goniometer.

the uniformity of the basal spacing, as already pointed out as the basis for the solvation procedure. These problems must be solved before full use can be made of the increased precision in instruments now available.

At the present stage of development, the concentration of minerals in the sample is estimated by the intensity of the various diffraction lines (present in the powder pattern produced under conditions for maximum intensity) relative to that of the respective lines of standard patterns. The most suitable standard patterns are those prepared with synthetic mixtures of minerals in about the same proportion as the test samples. A wide variety of mineral series may occur in mineral colloids of soils. Usually three to five occur in each colloid, and a total of 20 or more mineral series are involved in the analyses of soil colloids in general (13). Preparation of synthetic mixtures for such a variety of minerals is simplified by the limitation of the mineral associations which are likely to occur in any soil colloid because of the weathering sequence (13). On this basis, an abridged list of standard mineral mixtures has been formulated (29).

Diffraction intensity in patterns of over-all low intensity which is thought to arise from crystal distortion can be apportioned on the basis of relative intensity of standards so that the various crystalline materials total 100 per cent. This procedure assumes that the weakness in intensity is a resultant of lattice imperfection and small particle size (*a* and *c* above) rather than the presence of amorphous materials (*b* above). This assumption is thought to be generally sound, at least through weathering stage 10 (13). Although the oxides and hydrates of alumina and iron in soils are usually at least partly crystalline (13), their occurrence in amorphous form is not unlikely. This would suggest caution in the procedure for reporting crystalline material as 100 per cent in soil colloids high in these oxides (weathering stages 11, 12, and 13).

THE GEIGER COUNTER X-RAY SPECTROMETER

The Geiger counter X-ray spectrometer which recently has been developed has proved extremely useful in the study of the gross mineral composition of soil fractions (15). The details of this instrument have been discussed by Buhler (3), Friedman (7) and Firth (6). Figure 3 illustrates the complete equipment, which consists of an x-ray generator, a motor-driven scanning unit, and a recorder upon which are reproduced the angles and intensities of the characteristic reflections from the sample. This apparatus can be used with sands, silts, or clays, and diffraction patterns obtained in about 35 minutes.

The method of comparison of unknown samples with standards is illustrated in figures 4 and 5.

REFERENCES

- (1) ALDRICH, D. G., ET AL. 1944 Hydration control of montmorillonite as required for its identification and estimation by x-ray diffraction methods. *Soil Sci.* 57: 215-231.
- (2) BOURBEAU, G. A., AND BERGER, K. C. 1948 Thin sections of soils and friable materials prepared by impregnation with plastic "castolite." *Soil Sci. Soc. Amer. Proc.* (1947) 12: 409-412.
- (3) BUHLER, J. S. 1944 X-ray diffraction an industrial tool. *Metals and Alloys*, Nov. 1944
- (4) COLEMAN, R., AND JACKSON, M. L. 1946 Mineral composition of the clay fraction of several coastal plain soils of southeastern United States. *Soil Sci. Soc. Amer. Proc.* (1945) 10: 381-391.

- (5) EMMONS, R. C. 1929 A set of thirty immersion media. *Amer. Mineral.* 14: 482-483.
- (6) FIRTH, F. G. 1945 The Geiger Muller X-Ray Spectrometer. X-ray Society, Marquette University, Milwaukee, Wis.
- (7) FRIEDMAN, H. 1945 Geiger counter spectrometer for industrial research. *Electronics* 18: 132-137.
- (8) GIESEKING, J. E. 1939 The mechanism of cation exchange in montmorillonite-beidellite-monttronite type of clay minerals. *Soil Sci.* 47: 1-13.
- (9) HELLMAN, N. N., ET AL. 1943 Further note on an x-ray diffraction procedure for the positive differentiation of montmorillonite from hydrous mica. *Soil Sci. Soc. Amer. Proc.* (1942) 7: 194-200.
- (10) HELLMAN, N. N., AND JACKSON, M. L. 1944 Photometric interpretation of x-ray diffraction patterns for quantitative estimation of minerals in clays. *Soil Sci. Soc. Amer. Proc.* (1943) 8: 135-143.
- (11) HENDRICKS, S. B. 1941 Base exchange of the clay mineral montmorillonite for organic cations and its dependence upon adsorption due to Vander Waals forces. *Jour. Phys. Chem.* 45: 65-81.
- (12) JACKSON, M. L., AND HELLMAN, N. N. 1942 X-ray diffraction procedure for positive differentiation of montmorillonite from hydrous mica. *Soil Sci. Soc. Amer. Proc.* (1941) 6: 133-145.
- (13) JACKSON, M. L., ET AL. 1948 Weathering sequence of clay-size minerals in soils and sediments: I. *Jour. Phys. Colloid Chem.* 52: 1237-1260.
- (14) JEFFRIES, C. D. 1947 A rapid method for the removal of free iron oxides in soil prior to petrographic analysis. *Soil Sci. Soc. Amer. Proc.* (1946) 11: 211-212.
- (15) JEFFRIES, C. D. 1948 The use of the x-ray spectrometer in the determination of the essential minerals in soils. *Soil Sci. Soc. Amer. Proc.* (1947) 12: 135-140.
- (16) LARSEN, E. S., AND BERMEYER, H. 1934 The microscopic determination of the non-opaque minerals. U. S. Geol. Survey Bul. 848.
- (17) MAC EWAN, D. M. C. 1944 Identification of the montmorillonite group of minerals by x-rays. *Nature* 154: 577-578.
- (18) MAC EWAN, D. M. C. 1946 The identification and estimation of the montmorillonite group of minerals, with special reference to soil clays. *Jour. Soc. Chem. Indust.* 65: 298-305.
- (19) MACKIE, W. Z., ET AL. 1948 Mineral crystal forms in soils observed in the electron microscope: I. *Soil Sci. Soc. Amer. Proc.* (1947) 12: 176-179.
- (20) MARSHALL, C. E., AND JEFFRIES, C. D. 1946 Mineralogical methods in soil research: I. *Soil Sci. Soc. Amer. Proc.* (1945) 10: 397-405.
- (21) NAGELSCHMIDT, G. 1941 The identification of clay minerals by means of aggregate x-ray diffraction diagrams. *Jour. Sci. Inst.* 18: 100-101.
- (22) PENNINGTON, R. P., AND JACKSON, M. L. 1948 Segregation of the clay minerals of polycomponent soil clays. *Soil Sci. Soc. Amer. Proc.* (1947) 12: 452-457.
- (23) SHEARER, J. 1944 X-ray powder diffraction camera. *Jour. Sci. Inst.* 21: 198-199.
- (24) TANNER, C. B., AND JACKSON, M. L. 1948 Nomographs of sedimentation times for soil particles under gravity or centrifugal acceleration. *Soil Sci. Soc. Amer. Proc.* (1947) 12: 60-65.
- (25) TRUOG, E., ET AL. 1937 Procedure for special type of mechanical and mineralogical soil analysis. *Soil Sci. Soc. Amer. Proc.* (1936) 1: 101-112.
- (26) TRUOG, E., ET AL. 1937 Mechanical and mineralogical subdivision of the clay separate of soils. *Soil Sci. Soc. Amer. Proc.* (1936) 1: 175-179.
- (27) VOLK, N. J. 1933 Formation of muscovite in soils and refinements in specific gravity separations. *Amer. Jour. Sci.* 26: 114-129.
- (28) WHITE, J. L., AND JACKSON, M. L. 1947 Glycerol solvation of soil clays for x-ray diffraction analysis. *Soil Sci. Soc. Amer. Proc.* (1946) 11: 150-154.
- (29) WILLIS, A. L., ET AL. 1948 Mineral standards for quantitative x-ray diffraction analysis of soil clays: I. *Soil Sci. Soc. Amer. Proc.* (1947) 12: 400-406.

METHODS OF MEASURING FIELD CAPACITY AND PERMANENT WILTING PERCENTAGE OF SOILS

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In its relation to plant growth, soil moisture usually is measured to answer one or more of the following questions: How much water is in the soil? How much water must be applied to wet the soil? How much water is available to plants? How tightly is the water held by the soil? The reason for the last question is sometimes indirect, because the amount of energy required to remove the unit mass or volume of water from a soil will, of course, indicate whether the water is available, if the value of the free energy or potential of the soil moisture at the moisture content at which plants wilt is known.

Many attempts have been made to determine suitable bases from which soil moisture contents can be reckoned. Soil moisture, unlike other properties of materials, is almost universally measured as mass of water per unit mass of dry soil. The ratio of water to dry soil, of course, without reference to some standard or base for comparison is, in itself, of little value. A soil may have a high moisture content, expressed either as a percentage on a dry-weight basis or as a ratio of volume of water to unit volume of dry soil; yet it will not be known whether the soil contains water that is available to plants or whether additional water can be stored in it. Usually the moisture content is measured by heating the soil to 105° or 110°C.

Two soil moisture conditions, which might be called *soil moisture constants*, are important considerations in connection with plant growth. In fact, the authors believe they are the only ones of any practical value in this regard.

The first of these, the field capacity, although affected by many factors, may be taken to be the maximum amount of water that can be stored in a soil. The other, the permanent wilting percentage, or the lower limit of readily available water, is constant for a given soil, as will be pointed out later.

This review deals only with these two conditions. No attempt is made to discuss the many other soil moisture conditions or methods of measuring them, except so far as they may be used as measures of the field capacity and the permanent wilting percentage.

FIELD CAPACITY AND FACTORS AFFECTING IT

The field capacity is the amount of water held in the soil after excess water has drained away and the rate of downward movement of water has materially decreased, which usually takes place within 2 or 3 days after a rain or irrigation in pervious soils of uniform structure and texture.

Soils may drain slowly for a long time after water is applied. This movement is so extremely slow as compared to the rate of extraction of water by plants that for practical purposes we can say that a soil under a given set of conditions has a certain field capacity. It may be considered as the starting point from

which plants begin to use water from the soil in the normal functions of growth and fruiting, although some water may be used while the soil is being irrigated and before the field capacity is reached.

Of the numerous factors affecting field capacity, the most important are soil texture, uniformity, and depth. If, for example, a fine-textured soil (2) overlies a coarse soil, the zone immediately above the coarser layer will have a higher capacity than the clay would have if it were uniform throughout. And again, a shallow soil holds more water in a unit depth at field capacity than a deep soil of the same kind, but this effect is not marked in soils deeper than about 2 feet.

Colman (22) believes that a soil must be wetted 12 to 30 inches before the surface layer will have a moisture content as high as its field capacity, and that shallow field irrigations or irrigation and drainage of short soil columns in the laboratory do not necessarily provide valid measures of the field capacity. He has reported, however (23), that when small soil blocks are drained on a porous ceramic cell under a moisture tension of $\frac{1}{3}$ atmosphere, the moisture retained in the blocks could be related to the field capacity of the same soils determined under natural conditions.

Actually the field capacity is not an equilibrium value, but one on a time-drainage curve. Its position on the energy-soil-moisture-content curve, in the region where the curve is almost horizontal, further suggests that the field capacity is not a unique value.

MOISTURE EQUIVALENT AND ITS MEASUREMENT

The moisture equivalent is the most commonly used laboratory characterization of soil moisture conditions and measure of field capacity. Its measurement was first suggested by Briggs and McLane (17) and later modified by Briggs and Shantz (18).

Since the method is arbitrary and the results obtained are largely dependent on the procedure used in its determination, considerable attention has been given to it. The size of sample used, or more exactly the height of the column of soil in the centrifuge cup, has been shown (43, 64, 79, 80) to affect the average moisture content of the centrifuged sample.

Various other factors that affect the moisture equivalent determination have been studied (82), but size of sample, oven-drying, and fragmenting the sample are the most important.

The moisture equivalent seems to be a fairly reliable measure of texture of the soil. A number of formulas have been suggested to indicate its relation to the mechanical analysis (1, 6, 18, 53, 75).

Many have reported results of tests which indicate that the moisture equivalent is a close approximation of the field capacity (20, 52, 56, 69, 83), but below 12 to 14 per cent, the moisture equivalent seems to be less than the field capacity (83). It is a fair measure of the field capacity of fine-textured soils, but not necessarily of the sands.

Bouyoucos (11, 12) suggested a simple method of determining the amount

of water retained by a soil sample when subjected to suction in a small Büchner funnel. He called this moisture percentage the *moisture equivalent*.

A comparison of the values determined by the centrifugal moisture equivalent and those by means of the suction method was made by Pinckney and Alway (55). These workers reported that their results did not fully support Bouyoucos' conclusions as to the reliability and general desirability of the method. The authors found from tests on 53 soils that the ratio of moisture equivalent to suction values varied from 0.31 to 1.38.

It may be well to point out, in connection with the objection to calling the suction values *moisture equivalents*, that the latter are approximately equal to the field capacities of fine-textured soils, but not always to those of sands, and since in the centimeter-gram-second system the pull of gravity on unit mass is numerically equal to the pressure of 1 atmosphere, it is sometimes reasoned that the potential at the moisture equivalent is equal to a tension of 1 atmosphere. The fact that the pull of gravity on unit mass is approximately numerically equal to a pressure of 1 atmosphere is purely coincidental. It has the dimensions of force per unit mass, whereas pressure has the dimensions of force per unit area, and for potential energy per unit mass.

Schofield (67) varied the Bouyoucos suction method by placing a suspension of fine silt on the filter paper in the Büchner funnel before the soil was applied. The thin layer of silt allows water to pass through readily while air will not. Botelho da Costa and Alves (10) reported that increasing the thickness of the soil layer on the filter paper to about 6 mm. gave a fairly close measure of the moisture equivalent.

Richards and Weaver (62) found that the moisture retained by samples placed on a suction plate at a tension of $\frac{1}{3}$ atmosphere corresponds closely to the moisture equivalents.

In some cases it may be hazardous to use laboratory methods to measure field properties of soils (77). Instances of compactness so great that roots cannot penetrate the soil have been reported (86). Moisture equivalents made on the fragmented samples taken from the field do not agree with the field capacities. When moistened for the laboratory determination, the soils apparently did not again become so compact as in the field.

Determinations of moisture-holding properties of soils by physical or biological means may be unreliable indexes of field-moisture conditions for highly compacted soils. In fact, it may be impossible to make such determinations by usual biological means. Physical measurements also may give incorrect readings because the soil is disturbed by inserting the apparatus for the reading.

Bouyoucos (14) has suggested that the moisture equivalent and permanent wilting percentage could be determined simultaneously by measuring the water which failed to freeze in a dilatometer when the soil was supercooled to $-1.0^{\circ}\text{C}.$, then frozen at $-10^{\circ}\text{C}.$, and brought back to $-1.0^{\circ}\text{C}.$ He pointed out that the centrifuge method gives higher values than the dilatometer method, but expressed the belief that the latter is free from the influences of external factors and is less empirical than the former.

Anderson and Edlefsen (5) pointed out that the dilatometer method is not simple and care must be used in interpreting the results obtained with it.

PERMANENT WILTING PERCENTAGE AND ITS MEASUREMENT

The lower limit of available water—the wilting coefficient (18) or the permanent wilting percentage (38)—is the only other soil moisture condition of importance for consideration of the growth of plants. When soil moisture is reduced to the point where plants permanently wilt, further extraction of water does not cease, although the soil moisture content when plotted against time gives curves that are almost horizontal after the permanent wilting percentage is reached (39, 88).

Although various stages or degrees of wilting of plants might be recognized, only one, permanent wilting, represents a fairly definite condition. It has been defined (18) as that stage at which the leaves first undergo a permanent reduction of their moisture content because of a deficient supply of soil moisture. This means a condition from which the leaves do not recover in an approximately saturated atmosphere without addition of water to the soil.

The percentage of water in the soil at permanent wilting is of such importance that it deserves special consideration to be sure it is a satisfactory base from which to reckon soil moisture contents. Briggs and Shantz (18), who studied 20 soils and made some 1,300 trials, concluded that on a given soil all plants reduce the moisture content of the soil to about the same extent when permanent wilting is attained. The authors' results substantiate those conclusions. When a wide variety of plants were grown in cans on given soils, and a number of different soils were tested, the permanent wilting percentage was found to be a characteristic of the soil and not of the plant. Furthermore, crops of different kinds grown in the same fields during successive years have reduced the moisture of the soil in contact with their roots to the same percentage when allowed to wilt permanently. The authors have grown sunflower plants in small containers as a laboratory procedure to determine the permanent wilting percentage of soils for field trials with commercial agricultural crops of various sorts (39) and have obtained agreement when the field soil is uniform or nearly so. Lane and McComb (46) have concluded, however, from results of experiments with plants grown in pots, that the permanent wilting percentage is lower for grass than for trees.

The permanent wilting percentage can be determined directly by either of two methods.

The first, which is chiefly of value in regions of rainless summers, is by a system of regular soil sampling during the season. When the curves of the soil moisture contents are plotted against time, the percentage at which the curves become nearly horizontal, indicating that extraction of moisture has nearly ceased, may be taken as the permanent wilting percentage. Though the permanent wilting percentage obtained in this way is accurate and is reproducible in succeeding years, it has the disadvantage of being found comparatively late in the season. To determine whether the curve of moisture

extraction is horizontal or nearly so, several points are necessary, and the plants must remain wilted for at least several days with possible injury to them.

The second method is by bringing samples of the soil into the laboratory and growing indicator plants in them. The laboratory method found to be most practical for determining the permanent wilting percentage of soils is to raise dwarf sunflower plants in the soil in small tin cans.

Since discrepancies in the results obtained by the field and the laboratory methods sometimes do occur, a study of the factors responsible for them was made (39). Layers or pockets of soil of different texture at irregular depths below the surface and inadequate root distribution of permanently rooted crops (95), or of annual plants before the root system is fully developed, are the causes of some of the discrepancies. Soils may be so compact that roots cannot penetrate them (86, 87) although the density may not be high enough to be manifest or to warrant classification of the soils as hardpans. Consequently, the moisture content of these soils remains about the same throughout the season.

These studies (39) showed that the permanent wilting percentages were the same whether the determinations were made on entire plants or on plants with a single leaf or a pair of leaves or whether large or small containers were used; they were not affected by temperature except where the soil was kept at 41°F. and where it was raised to a relatively high temperature by direct sunlight on the metal containers.

Not all leaves on a plant wilt at the same time; therefore, judgment must be exercised in determining what part or parts of the plant should be used as a criterion of wilting. Should the whole plant, the bottom, or some particular pair of leaves be used? It is impossible to tell whether a plant has gone beyond permanent wilting. If it has not reached the permanent wilting percentage, however, it will recover when placed in a moist chamber. Permanent wilting percentages obtained with plants in containers may be too low instead of too high, because we have a satisfactory test or check on plants that are not wilted, but we do not have a check on those that have gone beyond permanent wilting.

The various ranges of soil moisture contents between the first evidence of drooping and permanent wilting are illustrated in figure 1. The suddenness with which wilting takes place, as shown in this figure, would be expected from the curves showing the relation between the tightness with which the water is held by the soil and the soil moisture content which shows a great increase in resistance to removal of the water in the region of the permanent wilting percentage. It also supports the finding that the permanent wilting percentage is a characteristic of the soil and not of the plant because, even though some plants may exert greater pull on the soil moisture than others, the resistance to removal increases, after the permanent wilting percentage is reached, at a rate that would more than overcome the greater pulling power of the plant.

Briggs and Shantz (18) suggested a number of indirect methods of determining the wilting coefficient. In the one most commonly used, the moisture equivalent is divided by the factor 1.84, but this relation does not hold for all soils (28, 81).

The ratios of moisture equivalents to permanent wilting percentages are variable and, although there is a high correlation between the two values, the departures from a mean value are so great for certain soils in so many cases that the use of any ratio is questionable. Schofield and Botelho da Costa (66) reported a soil with a ratio of 8. Wadsworth (90) found some of the Hawaiian soils have ratios as low as 1.11.

The authors proposed the term *permanent wilting percentage* in place of *wilting coefficient*, since the latter infers a definite relation to the other soil properties, as suggested by Briggs and Shantz, which it is now known does not hold for all soils.



FIG. 1. SIX SUNFLOWER PLANTS GROWING ON THE SAME AMOUNT OF FRESNO SAND ILLUSTRATE THE NARROW RANGE OF SOIL MOISTURE CONTENTS WITHIN WHICH WILTING TAKES PLACE

The gross weights of the cans and the soil moisture percentages are:

Can Number	97	105	101	91	102	104
Gross weight	gm 841.1	843.1	843.9	815.3	847.0	847.3
Moisture	per cent 3.3	3.6	3.7	3.9	4.1	4.1

Plants 104 and 102 are turgid; 94 shows a slight drooping of first leaves, 101 is in a more advanced stage of wilting; 105 is permanently wilted, and 97 has passed this stage.

Unless it is clearly stated, when the term *wilting coefficient* is used, the actual value is meant or whether the value is calculated from some other measured one, there will be uncertainty as to its accuracy. *Permanent wilting percentage*, or *p. w. p.*, is now in fairly wide use. Some prefer to shorten this to *wilting percentage* or *wilting point*.

The permanent wilting percentage is not a unique value but is a small range of soil moisture contents within which permanent wilting takes place. It has been shown (39) that this range need not exceed 1 per cent for fine-textured soils or 0.5 per cent for coarse-textured ones.

In small containers, extraction of water continues at a fairly rapid rate, after plants have wilted, up to or even after death. This has led to the concept of a wilting range and an ultimate wilting point. Taylor, Blaney, and McLaughlin

(78) have defined the latter as the soil moisture content when all the leaves have wilted, and the former as the range in moisture content of the soil between the wilting coefficient and the ultimate wilting point. Furr and Reeve (35) have suggested the term *first permanent wilting percentage* to mean "that percentage of soil moisture at which the forces acting on the water in the soil are at approximate equilibrium with the forces acting on the water in a plant which is at that stage of turgor at which vegetative growth practically ceases."

The authors have shown (39) that soil moisture extraction curves plotted from results with permanently rooted plants under field conditions slope downward approximately uniformly until they reach a moisture content at which there is a marked reduction in rate of extraction. This change in direction of the curve occurs slightly above the permanent wilting percentage obtained with sunflowers in containers. After reaching this moisture content the curves, from results in the field, continue nearly horizontal, showing that the soil moisture is slowly reduced to a minimum which is slightly below the permanent wilting percentage. This reduction is small, often no more than 1 per cent even after 3 or 4 months. These extraction curves coincide year after year as to minimum moisture content. The wilting range under field conditions is too small to be of practical importance.

Caldwell (21) and Shive and Livingston (72) disagreed with Briggs and Shantz in their concept that the residual soil moisture at permanent wilting was constant, and they believed that permanent wilting was determined by climatic and not by soil moisture conditions.

The authors have found (84) that the permanent wilting percentage is remarkably constant for any given soil under any evaporating condition likely to be obtained with plants growing in the field. Furr and Reeve (35) reported similar results.

Selection of the permanent wilting percentage as the critical moisture content is justified by the fact that any moisture above it is readily available to plants. As further substantiation, experiments with fruit trees show that size and quality of fruit and growth of the trees are not changed so long as the soil moisture content is above the permanent wilting percentage (40, 41).

PHYSICAL MEASUREMENTS OF SOIL MOISTURE CONSTANTS

The energy necessary to remove the water from the soil can be measured. Terms such as *free energy* (33), *pF* (67), *capillary potential* (19), *moisture potential* (27, 85), *thermodynamic potential* (36) *total potential*, and *soil moisture stress* (89) are used. The value will be referred to here simply as *potential*.

Whether it is a continuous function of soil moisture or a multiple-valued one has received much attention (37, 58, 76, 85, 91). Edlefsen (29) failed to find evidence of a hysteresis loop. Edlefsen and Smith (34) pointed out that the difference between a real hysteresis or multiple value and a lag in equilibrium must be clearly distinguished and, further, that hysteresis under field conditions is of little importance. Repeated sampling for soil moisture in a given field gives reproducible values. The soil is wetted by rains or irri-

gation and the starting point of measurement is always from wetted soil. The cycle is repeated as the soil is rewetted and sampled again during the drying process.

Because some of the methods used in plant-soil-water-relation studies do not measure soil moisture content directly but are dependent upon the potential, it is important to know the amount of energy required to remove water from the soil at the time when the moisture content is reduced to the permanent wilting percentage.

So far as can be judged from existing data, the potential of the soil moisture at the permanent wilting percentage is the same for all soils, although this may be open to question due to limitations of the methods now available to determine it. Vapor-pressure measurements (30, 79), freezing-point depression determinations (67), and dilatometer measurements (5, 13) indicate that about 16×10^6 ergs per gram is required to remove unit mass of water from a soil at the permanent wilting percentage.

Richards, by means of the pressure-membrane apparatus (63), has taken the value as equivalent to that required to remove water from a 15-atmosphere solution (62).

Removal of water by plants from media of known osmotic concentration

Shull (73) used small natural osmometers, *Xanthium* seeds, placed in contact with soils at known moisture contents, and concluded that about the same amount of energy would be required to remove water from a solution with an osmotic value of 4 atmospheres as from a soil at the wilting coefficient. The authors' results (84), though variable with this method, indicate much higher values than those reported by Shull.

Plants were grown in nutrient solutions to which sucrose was added to increase the osmotic values, and the concentrations at which wilting was produced were determined. The procedure was to raise plants in sand cultures and transfer them to the test solutions. Sometimes the plants could not be transferred directly into the high concentrations without wilting, but had to be placed in dilute solutions first and finally into the more concentrated ones through successive steps. It was also necessary to agitate or aerate the solutions.

Sugar beet plants were grown in sand until they had developed 4 or 5 leaves. Then they were transferred to a nutrient solution of 4 atmospheres and allowed to stand for 2 days. They were then put into 8-atmosphere solution for 24 hours. The concentrations of the sugar solutions in which they were finally placed varied from 8 to 22 atmospheres (fig. 2). The plants were able to take water without apparent difficulty from solutions up to a concentration of about 16 atmospheres at room temperature.

Sunflowers were grown on fine sand in pots and then allowed to wilt permanently. The sand was then leached with sugar solution. The appearance of the plants 5 days later is shown in figure 3. The concentration was adjusted so that at the temperature in the greenhouse the solution would have osmotic

values ranging from 6 to 18 atmospheres. All of the plants in the solution with concentrations up to 14 atmospheres seemed to have fully recovered; those at 16 atmospheres showed some wilt; and those at 18 atmospheres failed to recover.

These tests by biological means and those by physical methods, although both lack preciseness, indicate that the resistance to removal of water at the permanent wilting percentage is close to 16×10^6 ergs per gram.



FIG. 2. EFFECT OF OSMOTIC CONCENTRATION OF SOLUTION ON UPTAKE OF WATER BY PLANTS

Ninety-six hours after transfer of sugar beet plants to sugar solutions. The plants in first and second jars from the left, at 10 and 14 atmospheres, are fully turgid; those in the third jar, at 16 atmospheres show some wilting; and those in the other jars, at 18, 20, and 22 atmospheres failed to recover.



FIG. 3. EFFECT OF CONCENTRATION OF LEACHING SOLUTION ON PERMANENTLY WILTED SUNFLOWER PLANTS GROWN IN FINE SAND

The sand in the pots was leached with sugar solutions which, at the greenhouse temperature, had concentrations of, left to right, 6, 8, 10, 12, 14, 16, and 18 atmospheres. Those at 16 atmospheres show evidence to slight wilting. The plants in the last pot did not recover. Photo taken 5 days after leaching with the solutions.

The principal physical methods of determining the potential of soil moisture with special reference to the permanent wilting percentage are by measurements of vapor pressure, freezing-point depression, retention against centrifugal force, heat of wetting, osmotic membrane, suction on porous media or porous porcelain, and retention of water by samples placed on membranes and against positive pressures.

Vapor pressure measurements

Many investigators have discussed methods of measuring the aqueous vapor pressure of soils (30, 57, 79, 92). The method most commonly used, called the *static method*, is to place soil samples, usually about 5 gm., in small cans or dishes in vacuum desiccators over sulfuric acid solution of known concentration at constant temperature. The time of exposure of the samples varies in different laboratories. The length of time required for attainment of equilibrium between the soil and solution of known vapor pressure is a serious objection to the method.

Kuron (45) showed slow absorption of water up to 40 days at various vapor pressures. Day (26) also showed that with pairs of samples, one moistened to the moisture equivalent and the other air-dried, and both allowed to remain 23 days in an evacuated desiccator, the preliminary moisture content had an appreciable influence on the final values obtained.

Puri *et al.* (57) has further pointed out that the difficulties with high relative humidities are too great for satisfactory results. Linford (48) showed the prac-

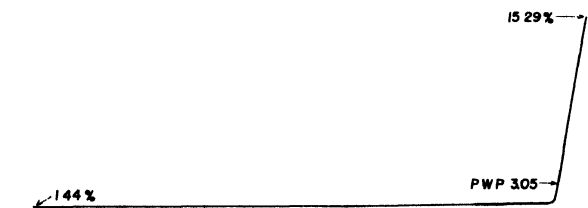


FIG. 4 RATE OF DRYING CURVE FOR A SANDY LOAM OVER A 44 PER CENT SULFURIC ACID SOLUTION DURING AN 8-DAY PERIOD

Initial moisture content 15.29 per cent, permanent wilting percentage 3.05. The final moisture content, 1.44 per cent, is not an equilibrium value.

tical impossibility of obtaining equilibrium between a soil and a saturated vapor drier than complete saturation of the soil.

Edlefsen (30) proposed exposing samples of soil in a vacuuated system in which the vapor pressure is measured by reference to the conductance of a glass-wool cell previously calibrated by exposure to various relative humidities.

A striking example of the increase in resistance to removal of water from the soil when the moisture content is in the region of the permanent wilting percentage is shown in figure 4, a photograph of a rate of drying curve for a sandy loam soil. A sample containing about 3 gm. of dry soil which had been wet to a moisture content of 15.29 per cent was placed in a small can and suspended over a 44 per cent sulfuric acid solution by means of wire led through a hole in a rubber stopper in the lid of a desiccator. The wire was attached to the pan of a balance which was equipped with an automatic attachment so that losses of weight of the sample in the desiccator could be weighed automatically and recorded on a piece of photographic paper. The position of the permanent wilting percentage, 3.05, is indicated on the curve. The curve is linear down to a moisture just below the permanent wilting percentage and shows the marked increase in tightness with which the water is held after it is reached.

This evidence, together with the results of other physical measurements, as well as those of the effects of different soil moisture conditions on plant growth, the authors believe, justifies the selection of the permanent wilting percentage as a critical soil moisture constant.

It has been proposed that water absorption values may be used to determine soil moisture constants by multiplying the percentage of water, say over 3.3, 10, or 44 per cent sulfuric acid solution, by a coefficient, but the fact that the vapor pressure curves for different soils are not parallel suggests the futility of this procedure.

Freezing-point depression measurements

Freezing-point depression measurements can be used to determine the potential, but the usual Beckmann technique is limited to relatively high moisture contents in contrast to the static vapor pressure method, which is suitable to only low moisture contents.

Schofield (67) has discussed methods of measuring the potential of soil moisture, and Botelho da Costa and he (9, 66, 68) have suggested methods of determining the wilting coefficient by the freezing-point method.

Schofield suggests the term pF to designate the free energy of the soil moisture. It is the logarithm of the height in centimeters of the water column which the water in the moist soil could support when properly connected to a water supply. Schofield used freezing-point depression measurements with soils of low moisture contents.

To overcome some of the difficulties of the Beckmann technique, Bodman and Day (7, 8) developed a method in which the temperature was determined by means of thermocouples calibrated so that temperature could be observed by electromotive force of the thermocouple circuit or by galvanometer deflection.

Bodman and Day expressed the belief that the energy of retention at the permanent wilting percentage is approximately 18×10^6 ergs per gram. Schofield and Botelho da Costa selected 16×10^6 ergs per gram for this value. The latter reported (68) that the freezing-point method can be used confidently for indirect determination of the wilting coefficient only in soils having a salt content under 500 p.p.m., a pF at the moisture equivalent under 3.4, and a freezing-point depression, when saturated, less than 0.07°C .

The authors' experience with freezing-point depression measurements has not been entirely satisfactory. In figure 5 freezing-point curves for six soils are shown. Two of these, OL₂ and 25₁, have freezing points at the permanent wilting percentage which do not correspond with the others or with those of other soils in other trials, which were found to be -1.4° or -1.5°C . The freezing point of soil 25₁ at the permanent wilting percentage of 3.6 would be about -4.5°C . To raise the freezing point 3°C ., removal of salt to the extent of 36 atmospheres would be required; in other words, in place in the field, 7,340 pounds of NaCl, or about 0.17 per cent by weight, would have to be leached out of each acre-foot of soil. Since the citrus orchard from which the soil was taken is vigorous, and productive, it seems unlikely that it could contain this much salt without show-

ing toxic effects. The freezing point of soil OL₂ with a permanent wilting percentage of 7.1 would have to be lowered from 0.7° to -1.5°C. This would require addition of salt to the extent of 9.65 atmospheres, or 5,670 pounds of NaCl per acre-foot.

Retention of water against centrifugal force

Another method of measuring the potential of soil moisture at various moisture contents is by determining the retention of water against centrifugal forces of known magnitude. The only wide use of this method is at the centrifugal force of 1,000 times gravity to determine the moisture equivalent. Lebedeff (47) and Olmstead (54) described methods of centrifuging soils at high speeds, and Russell

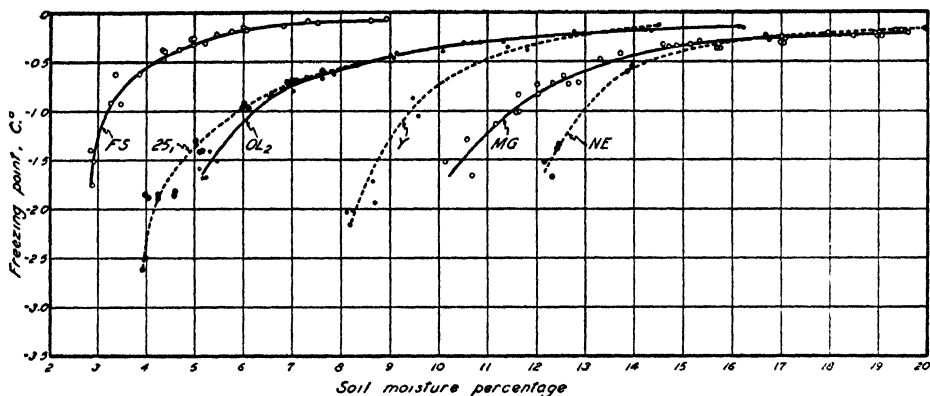


FIG. 5. FREEZING POINTS AND MOISTURE CONTENTS OF SIX SOILS

The permanent wilting percentages of the soils are: FS, 3.0; 251, 3.6; OL₂, 7.1; Y, 8.9; MG, 10.3; and NE, 12.0.

and Richards (65) suggested means to determine moisture retention by centrifuging with special reference to the moisture equivalent and permanent wilting percentage.

Heat of wetting measurement

The fact that heat is released when water is condensed on the surface of soil particles makes it possible to determine the pressure required to produce the heat. The calculation can be made by means of the known relation between the temperature rise of water with pressure. This method is applicable only to soil moisture well below the permanent wilting percentage and therefore is of little value for determining constants for plant growth.

Measurement of absorption of water by porous material

Measurement of the amount of water absorbed by porous media or porous porcelain pieces has been suggested for determining the field capacity and permanent wilting percentage of soil.

Livingston and Koketsu (49) used small hollow cylinders of porous porcelain, which they called *soil points*. All but a small portion of the cone-shaped end of

the cylinder is waterproofed, and this surface can be brought into close contact with the soil to be tested. The soil points are inserted into the soil at the desired depth, left for a stated period, usually 60 minutes, removed, and then the moisture content is determined by weighing and drying. Livingston *et al.* (50, 94) have investigated further the use of porous porcelain absorbers. Richards, using porous porcelain similar to Livingston's soil points or autoirrigators (59), developed an apparatus called a *tensiometer*. Such devices have not been developed to measure moisture contents down to the permanent wilting percentage, but they can be used to measure the field capacity (62).

Davidson and Schofield (24) used small pieces of Portland stone which are calibrated against known pressures for suctions of less than 1 atmosphere and by exposure in sealed containers to known vapor pressures. The calibrated stones are placed, for 24 hours, in contact with the soil to be tested and are then weighed. By reference to the calibration curves, the suction produced by the stone plates can be measured.

Slater and Bryant (74), Richards and Weaver (61), and Davis and Slater (25) have suggested the use of absorbers like the Livingston soil points to measure soil moisture. Comparison of tensiometers, electrical resistance of porous blocks (15), and gravimetric plugs led Slater and Bryant to the conclusion "that tensiometers are decidedly limited in usefulness, that under a majority of soil conditions gravimetric plugs are best adapted to accurate measurement, and that resistance blocks are best adapted to semiquantitative measurements of the variable field moisture of large areas under conditions that do not require the improved accuracy that can be obtained by temperature corrections."

Kelley *et al.* (44) compared results obtained with sorption blocks, tensiometers, Bouyoucos electrical resistance blocks, and methods which depend upon the heat properties of soil or porous media in moisture equilibrium with the soil (70, 71). They concluded "that Bouyoucos blocks are the most practical instruments available at the present time for measuring moisture changes at tensions above 1 atmosphere in soils not containing large amounts of salts," and that gravimetric sorption blocks are not so satisfactory as the Bouyoucos blocks because of the considerable lag in approaching equilibrium. They reported that "the thermal unit is not as useful for following moisture changes as either the tensiometer or Bouyoucos blocks."

Johnston (42) obtained comparable readings with a permeable jacket around heater elements of thermal radiators at field capacities and permanent wilting percentages in two very different soils.

Methods have been proposed in which the electrical conductivity of a soil itself has been studied, but the salinity of the soil, temperature, and variation in contact resistance affect the results to such an extent they have been discouraging (16, 31, 51, 93).

Measurements of the electrical conductivity of porous blocks (3, 15, 32) indicate that it is approximately the same at the permanent wilting percentage for all the soils tested. Dielectric constant measurements (4) also show that this relation holds.

Pressure membrane method

Richards (63) has perfected an apparatus by which water can be forced from soils under high pressures. The soil is placed on a cellophane membrane with fine pores, and the water is forced out of the soil by applying air or gas pressure. The relation of the water retained by the soil under a pressure of 15 atmospheres (60) to the permanent wilting percentage has been studied. Though there is a high correlation between the two values, some soils have permanent wilting percentages which do not agree with the moisture retained against 15 atmosphere pressure.

Richards and Weaver (62) and Wadleigh (89) have discussed the effect of dissolved substances on the potential of soil moisture and on the permanent wilting percentage. Wadleigh defined the total soil moisture stress as the soil moisture tension in atmospheres plus the osmotic pressure of the soil solution in atmospheres. A soil moisture tension curve was constructed from measurements of the pressure membrane apparatus. The osmotic pressure of the soil solution was determined at one moisture content by extracting with the pressure membrane apparatus, determining freezing-point depressions of the solution, and assuming osmotic pressure is a straight line function of moisture content.

It is to be expected that addition of soluble material will change the soil moisture constants. When relatively large amounts are added to soils which already contain appreciable quantities of salts, the moisture equivalents and permanent wilting percentages may be affected. Of course, the permanent wilting percentage determined biologically or by measurement of the potential of the soil moisture should show the effect of such treatment. The authors have found, however, that applications of common fertilizer materials, even in excess of amounts practical under field conditions, have not changed the moisture equivalent or permanent wilting percentage of soils that may be classed as nonsaline. Toxic effects, of course, are sometimes evidenced even with small additions of some materials.

SUMMARY

Two soil moisture constants are of importance in relation to plant growth: the field capacity and the permanent wilting percentage. The former is affected by so many factors that, precisely, it is not a constant, yet it does serve as a practical measure of soil water-holding capacity. The latter is a constant. It is characteristic of the soil and is independent of environmental conditions such as are likely to occur in the field and under which wilting of plants takes place.

The field capacity may be measured in the field by sampling shortly after water is applied. Such measurements are reliable if the soil is uniform in texture. The field capacity, when obtained by field sampling, is a better value of moisture retained by a soil after rain or irrigation than is the moisture equivalent. The chief difficulty with the field capacity is the inconvenience in obtaining it.

The moisture equivalent is a fairly accurate measure of field capacity for fine-textured red soils, but not always for sands. The agreement is good for soils with moisture equivalents above 12 to 14 per cent. The moisture equivalent is not a reliable value from which to calculate the permanent wilting percentage.

The selection of the permanent wilting percentage as a base for reckoning soil moisture has much to commend it. It has been shown that moisture-extraction curves for plants the roots of which thoroughly explore the soil slope downward approximately uniformly until the permanent wilting percentage is reached, thus indicating that water is readily available to the plants throughout the range of moisture from the field capacity to the permanent wilting percentage. After the permanent wilting percentage is reached, the curves become almost horizontal, and there is very little further extraction of moisture even though the water supply is not replenished for long periods.

Field experiments, especially with orchard trees, have shown that size and quality of fruit and growth of trees are not changed so long as the moisture is above the permanent wilting percentage, a further reason why this is the critical moisture constant.

The permanent wilting percentage can be obtained by sampling the soil regularly during the season and noting the percentage of moisture at which the extraction curves become nearly horizontal. It can also be determined in the laboratory by growing indicator plants in small containers and determining the soil moisture content at which the plants permanently wilt.

The potential of the soil moisture at the permanent wilting percentage is approximately 16×10^6 ergs per gram. Physical methods which can measure potentials of this amount, then, lend themselves to indirect determination of the permanent wilting percentage.

It has been pointed out, however, that both the biological method of growing indicator plants and the use of physical measurements to find the permanent wilting percentage may be misleading under certain conditions. For example, roots do not penetrate soils of high density, and the change in moisture content may simply be due to slow drainage. Fragmenting the soil either in taking the sample or inserting measuring devices may give misleading results.

The principal physical methods with their limitations may be listed as follows:

Vapor-pressure measurements should give accurate indication of the total potential of soil moisture. This method works best at low moisture contents and not very well at high ones. The time required for attainment of equilibrium between soil and the measuring solution is excessive.

Water absorptive values obtained for a soil at certain vapor pressures cannot be multiplied by a coefficient to estimate the probable value at a higher or lower vapor pressure unless the vapor-pressure curve for each soil is determined.

Freezing-point measurements also should give values for the total potential of the soil moisture, but they are very difficult to make at low moisture contents. Agreement with the permanent wilting percentage and freezing point lowering of about 1.4° or 1.5°C . is not good for some soils. Salinity of the soil may be the cause for these exceptions, although in at least two soils this does not seem to be the case.

Retention of water by the soil against centrifugal force as a measure of soil moisture constants has been limited largely to one value, the moisture equivalent. Mechanical difficulties at the high speeds required to remove water below this amount have been discouraging.

The heat of wetting method can be used for low moisture contents, but not in the high range. It has received little attention.

The use of small natural osmometers, *Xanthium* seeds, in the Shull method has been limited. Although the results are variable, a fairly good curve can be obtained at low moisture contents. With most soils germination of the seeds is troublesome.

Suction measurements on porous media or plates are limited to high moisture contents at suctions of less than 1 atmosphere. The lag in time until equilibrium between the absorbing medium and the soil is a deterrent to use of porous porcelain absorbers.

Use of a combination of porous absorbers which have been calibrated by suction measurements in the low range of suction values and by vapor-pressure measurements at high ones is also subject to the disadvantages of porous absorbers.

The pressure-membrane apparatus perfected by Richards has promise, but there is not always agreement between the water retained at 15 atmospheres and the permanent wilting percentage.

Electrical resistance and dielectric constant of porous blocks and thermal conductivity have been used to measure the tightness with which water is held by the soil by reference to a calibration curve for each instrument, but some details must be worked out for this type of measurement before complete success in practice will be possible.

REFERENCES

- (1) ALWAY, F. J., AND RUSSEL, J. C. 1916 Use of the moisture equivalent for the indirect determination of the hygroscopic coefficient. *Jour. Agr. Res.* 6: 833-846.
- (2) ALWAY, F. J., AND MCDOLE, G. R. 1917 Relation of movement of water in a soil to its hygroscopicity and initial moistness. *Jour. Agr. Res.* 10: 391-428.
- (3) ANDERSON, A. B. C., AND EDLEFSEN, N. E. 1942 Laboratory study of the response of 2- and 4-electrode plaster of paris blocks as soil-moisture content indicators. *Soil Sci.* 53: 413-428.
- (4) ANDERSON, A. B. C., AND EDLEFSEN, N. E. 1942 The electrical capacity of the 2-electrode plaster of paris block as an indicator of soil-moisture content. *Soil Sci.* 54: 35-46.
- (5) ANDERSON, A. B. C., AND EDLEFSEN, N. E. 1942 Volume-freezing-point relations observed with new dilatometer technique. *Soil Sci.* 54: 221-232.
- (6) BODMAN, G. B., AND MAHMUD, A. J. 1932 The use of the moisture equivalent in the textural classification of soils. *Soil Sci.* 33: 363-374.
- (7) BODMAN, G. B., AND DAY, P. R. 1938 The thermoelectric method of determining the freezing points of soils. *Soil Sci. Soc. Amer. Proc.* (1937) 2: 65-71.
- (8) BODMAN, G. B., AND DAY, P. R. 1943 Freezing points of a group of California soils and their extracted clays. *Soil Sci.* 55: 225-246.
- (9) BOTELHO DA COSTA, J. V. 1938 The indirect determination of the "wilting coefficient" by the freezing-point method, and the influence of the salts upon the pF at that critical moisture content. *Jour. Agr. Sci.* 28: 654-662.
- (10) BOTELHO DA COSTA, J. V., AND ALVES, J. 1942 The determination of the moisture equivalent by the silt-suction method and the shifting of the pF curve of stored soil samples. *Jour. Agr. Sci.* 32: 294-297.
- (11) BOUYOUCOS, G. J. 1929 A new simple and rapid method for determining the moisture equivalent of soils, and the role of soil colloids on this moisture equivalent. *Soil Sci.* 27: 233-241.
- (12) BOUYOUCOS, G. J. 1935 A comparison between the suction method and the centrifuge method for determining the moisture equivalent of soils. *Soil Sci.* 40: 165-171.
- (13) BOUYOUCOS, G. J. 1936 The dilatometer method as an indirect means of determining the permanent wilting point of soils. *Soil Sci.* 42: 217-223.
- (14) BOUYOUCOS, G. J. 1937 The dilatometer method for determining the moisture equivalent of soils. *Soil Sci.* 43: 385-389.
- (15) BOUYOUCOS, G. J., AND MICK, A. H. 1940 An electrical resistance method for the continuous measurement of soil moisture under field conditions. *Mich. Agr. Exp. Sta. Tech. Bul.* 172.

- (16) BRIGGS, L. J. 1899 Electrical instruments for determining the moisture, temperature, and soluble salt content of soils. *U. S. Dept. Agr. Div. Soils Bul.* 15: 1-35.
- (17) BRIGGS, L. J., AND McLANE, J. W. 1907 The moisture equivalent of soils. *U. S. Dept. Agr. Bur. Soils Bul.* 45: 1-23.
- (18) BRIGGS, L. J., AND SHANTZ, H. L. 1912 The wilting coefficient for different plants and its indirect determination. *U. S. Dept. Agr. Bur. Plant Indus. Bul.* 230: 1-83.
- (19) BUCKINGHAM, E. 1907 Studies on the movement of soil moisture. *U. S. Dept. Agr. Bur. Soils Bul.* 38: 1-61.
- (20) BURR, W. W., AND RUSSEL, J. C. 1925 Report of certain investigations on the central Nebraska Supplemental Irrigation Project. *Nebr. Dept. Pub. Works Bien. Rpt.* (1923-1924) 15: 198-240.
- (21) CALDWELL, J. R. 1913 The relation of environmental factors to the phenomena of permanent wilting. *Physiol. Res.* 1: 1-56.
- (22) COLMAN, E. A. 1944 The dependence of field capacity upon the depth of wetting of field soils. *Soil Sci.* 58: 43-50.
- (23) COLMAN, E. A. 1947 A laboratory procedure for determining the field capacity of soils. *Soil Sci.* 63: 277-283.
- (24) DAVIDSON, A. L. C., AND SCHOFIELD, R. K. 1942 Measurement of the suction of soil water by Portland stone absorbers calibrated by a new method for determining vapour pressures near to saturation. *Jour. Agr. Sci.* 32: 413-427.
- (25) DAVIS, W. E., AND SLATER, C. S. 1942 A direct weighing method for sequent measurements of soil moisture under field conditions. *Jour. Amer. Soc. Agron.* 34: 285-287.
- (26) DAY, P. R. 1941 The Moisture Potential of Soils by the Cryoscopic Method. Berkeley, Calif. (Doctorate thesis.)
- (27) DAY, P. R. 1942 The moisture potential of soils. *Soil Sci.* 54: 391-400.
- (28) DUNCAN, W. H. 1939 Wilting coefficient and wilting percentage of three forest soils of the Duke Forest. *Soil Sci.* 48: 413-420.
- (29) EDLEFSEN, N. E. 1933 A glass wool cell for measuring aqueous vapor pressure of soils. *Rev. Sci. Instruments* 4: 345-346.
- (30) EDLEFSEN, N. E. 1934 A new method of measuring the aqueous vapor pressure of soils. *Soil Sci.* 38: 29-35.
- (31) EDLEFSEN, N. E., AND ANDERSON, A. B. C. 1941 The four-electrode resistance method for measuring soil-moisture content under field conditions. *Soil Sci.* 51: 367-376.
- (32) EDLEFSEN, N. E., ANDERSON, A. B. C., AND MARCUM, W. B. 1942 Field study of the response of the electrical resistance of 2- and 4-electrode plaster of paris blocks to variations in soil moisture. *Soil Sci.* 54: 275-279.
- (33) EDLEFSEN, N. E., AND ANDERSON, A. B. C. 1943 Thermodynamics of soil moisture. *Hilgardia* 15: 31-298.
- (34) EDLEFSEN, N. E., AND SMITH, W. O. 1944 The determination of moisture in undisturbed soil. *Soil Sci. Soc. Amer. Proc.* (1943) 8: 112-115.
- (35) FURR, J. R., AND REEVE, J. O. 1945 Range of soil-moisture percentages through which plants undergo permanent wilting in some soils from semiarid irrigated areas. *Jour. Agr. Res.* 71: 149-170.
- (36) GARDNER, W. 1944 The role of the pF in the dynamics of soil moisture. *Amer. Geophys. Union Trans.* 1944: 699-712.
- (37) HAINES, W. B. 1930 Studies in physical properties of soils: V. *Jour. Agr. Sci.* 20: 97-116.
- (38) HENDRICKSON, A. H., AND VEIHMEYER, F. J. 1929 Irrigation experiments with peaches in California. *Calif. Agr. Exp. Sta. Bul.* 479: 1-56.
- (39) HENDRICKSON, A. H., AND VEIHMEYER, F. J. 1945 Permanent wilting percentages of soils obtained from field and laboratory trials. *Plant Physiol.* 20: 517-539.

- (40) HENDRICKSON, A. H., AND VEIHMEYER, F. J. 1946 Unnecessary irrigation as an added expense in the production of prunes. *Amer. Soc. Hort. Sci. Proc.* 48: 43-47.
- (41) HENDRICKSON, A. H., AND VEIHMEYER, F. J. 1948 Sizes of prunes as influenced by differences in set and irrigation treatment. *Amer. Soc. Hort. Sci. Proc.* 51: 235-238.
- (42) JOHNSTON, C. N. 1942 Water-permeable jacketed thermal radiators as indicators of field capacity and permanent wilting percentage in soils. *Soil Sci.* 54: 123-126.
- (43) JOSEPH, A. F., AND MARTIN, F. J. 1923 The moisture equivalent of heavy soils. *Jour. Agr. Sci.* 13: 49-59.
- (44) KELLEY, O. J., ET AL. 1946 A comparison of methods of measuring soil moisture under field conditions. *Jour. Amer. Soc. Agron.* 38: 759-784.
- (45) KURON, H. 1936 Die Abgrenzung der Formen des vom Boden gebundenen Wassers durch dessen Einfluss auf die Umsetzung zwischen Boden und Salzen. *Ztschr. Pflanzenernähr. Düngung u. Bodenk.* 45: 352-363.
- (46) LANE, R. D., AND MCCOMB, A. L. 1948 Wilting and soil moisture depletion by tree seedlings and grass. *Jour. Forestry* 46: 344-349.
- (47) LEBEDEF, A. F. 1928 Methods of determining the maximum molecular moisture holding capacity of soils. *First Internatl. Cong. Soil Sci. Proc.* 1: 551-563.
- (48) LINFORD, L. B. 1930 Soil moisture phenomena in a saturated atmosphere. *Soil Sci.* 29: 227-237.
- (49) LIVINGSTON, B. E., AND KOKETSU, R. 1920 The water-supplying power of the soil as related to the wilting of plants. *Soil Sci.* 9: 469-485.
- (50) LIVINGSTON, B. E., AND NOREM, W. L. 1937 Water-supplying power and water-absorbing power of soils as related to wilting of wheat and coleus in greenhouse pot cultures. *Soil Sci.* 43: 177-204.
- (51) MCCORKLE, W. H. 1931 Determination of soil moisture by the method of multiple electrodes. *Tex. Agr. Exp. Sta. Bul.* 426.
- (52) MATHEWS, O. R., AND CHILCOTT, E. C. 1923 Storage of water in soils and its utilization by spring wheat. *U. S. Dept. Agr. Bul.* 1139: 1-27.
- (53) MIDDLETON, H. E. 1920 The moisture equivalent in relation to the mechanical analysis of soils. *Soil Sci.* 9: 159-167.
- (54) OLMSTEAD, L. B. 1937 Some moisture relations of soils from the Erosion Experiment Stations. *U. S. Dept. Agr. Tech. Bul.* 562.
- (55) PINCKNEY, R. M., AND ALWAY, F. J. 1939 Reliability of the proposed suction method of determining the moisture equivalent of soils. *Soil Sci.* 48: 403-411.
- (56) PIPER, A. M. 1933 Notes on the relation between the moisture equivalent and the specific retention of water-bearing materials. *Amer. Geophys. Union Trans.* 1933: 481-491.
- (57) PURI, A. N., CROWTHER, E. M., AND KEEN, B. A. 1925 The relation between the vapour pressure and water content of soils. *Jour. Agr. Sci.* 15: 68-88.
- (58) RICHARDS, L. A. 1931 Capillary conduction of liquids through porous mediums. *Physics* 1: 318-333.
- (59) RICHARDS, L. A. 1942 Soil moisture tensiometer materials and construction. *Soil Sci.* 53: 241-248.
- (60) RICHARDS, L. A., AND WEAVER, L. R. 1943 The relation between the fifteen-atmosphere percentage and the permanent wilting percentage. *Soil Sci.* 56: 331-339.
- (61) RICHARDS, L. A., AND WEAVER, L. R. 1943 The sorption-block soil moisture meter and hysteresis effects related to its operation. *Jour. Amer. Soc. Agron.* 35: 1002-1011.
- (62) RICHARDS, L. A., AND WEAVER, L. R. 1944 Moisture retention of some irrigated soils as related to soil-moisture tension. *Jour. Agr. Res.* 69: 215-235.
- (63) RICHARDS, L. A. 1947 Pressure-membrane apparatus—construction and use. *Agr. Engin.* 28: 451-454.

- (64) RUSSEL, J. C., AND BURR, W. W. 1925 Studies on the moisture equivalent of soils. *Soil Sci.* 19: 251-266.
- (65) RUSSELL, M. B., AND RICHARDS, L. A. 1939 The determination of soil moisture energy relations by centrifugation. *Soil Sci. Soc. Amer. Proc.* (1938) 3: 65-69.
- (66) SCHOFIELD, R. K., AND BOTELHO DA COSTA, J. V. 1935 The determination of the pF at permanent wilting and at the moisture equivalent by the freezing-point method. *Trans. 3d Internatl. Cong. Soil Sci.* 1: 6-10.
- (67) SCHOFIELD, R. K. 1935 The pF of the water in soil. *Trans. 3d Internatl. Cong. Soil Sci.* 2: 37-48.
- (68) SCHOFIELD, R. K., AND BOTELHO DA COSTA, J. V. 1938 The measurement of pF in soil by freezing point. *Jour. Agr. Sci.* 28: 644-653.
- (69) SCOFIELD, C. S., AND WRIGHT, C. C. 1928 The water relations of Yakima Valley soil. *Jour. Agr. Res.* 37: 65-85.
- (70) SHAW, B. T., AND BAVER, L. D. 1939 Heat conductivity as an index of soil moisture. *Jour. Amer. Soc. Agron.* 31: 886-891.
- (71) SHAW, B. T., AND BAVER, L. D. 1940 An electrothermal method for following moisture changes of the soil *in situ*. *Soil Sci. Soc. Amer. Proc.* (1939) 4: 78-83.
- (72) SHIVE, J. W., AND LIVINGSTON, B. E. 1914 The relation of atmospheric evaporating power to soil-moisture content at permanent wilting of plants. *Plant World* 17: 81-121.
- (73) SHULL, C. A. 1916 Measurement of the surface forces in soils. *Bot. Gaz.* 62: 1-31.
- (74) SLATER, C. S., AND BRYANT, J. C. 1946 Comparison of four methods of soil moisture measurement. *Soil Sci.* 61: 131-155.
- (75) SMITH, A. 1917 Relation of the mechanical analysis to the moisture equivalent of soils. *Soil Sci.* 4: 471-476.
- (76) SMITH, W. O. 1933 The final distribution of retained liquid in an ideal uniform soil. *Physics* 4: 425-438.
- (77) SMITH, W. O. 1944 The effect of soil physical conditions on moisture constants in the upper capillary range. *Soil Sci.* 58: 1-16.
- (78) TAYLOR, C. A., BLANEY, H. F., AND McLAUGHLIN, W. W. 1934 The wilting-range in certain soils and the ultimate wilting-point. *Amer. Geophys. Union Trans.* 1934: 436-444.
- (79) THOMAS, M. D. 1921 Aqueous vapor pressure of soils. *Soil Sci.* 11: 409-434.
- (80) VEIHMEYER, F. J., ISRAELSEN, O. W., AND CONRAD, J. P. 1924 The moisture equivalent as influenced by the amount of soil used in its determination. *Calif. Agr. Exp. Sta. Tech. Paper* 16: 1-65.
- (81) VEIHMEYER, F. J., AND HENDRICKSON, A. H. 1928 Soil moisture at permanent wilting of plants. *Plant Physiol.* 3: 355-357.
- (82) VEIHMEYER, F. J., OSERKOWSKY, J., AND TESTER, K. B. 1928 Some factors affecting the moisture equivalent of soils. *Frist Internatl. Cong. Soil Sci. Proc. and Papers* 1: 512-534.
- (83) VEIHMEYER, F. J., AND HENDRICKSON, A. H. 1931 The moisture equivalent as a measure of the field capacity of soils. *Soil Sci.* 32: 181-193.
- (84) VEIHMEYER, F. J., AND HENDRICKSON, A. H. 1934 Some plant and soil-moisture relations. *Amer. Soil Survey Assoc. Bul.* 15: 76-80.
- (85) VEIHMEYER, F. J., AND EDLEFSEN, N. E. 1937 Interpretation of soil-moisture problems by means of energy changes. *Amer. Geophys. Union Trans.* 1937: 302-318.
- (86) VEIHMEYER, F. J., AND HENDRICKSON, A. H. 1946 Soil density as a factor in determining the permanent wilting percentage. *Soil Sci.* 62: 451-456.
- (87) VEIHMEYER, F. J., AND HENDRICKSON, A. H. 1948 Soil density and root penetration. *Soil Sci.* 65: 487-493.
- (88) VEIHMEYER, F. J., AND HENDRICKSON, A. H. 1948 The permanent wilting percentage as a reference point for the measurement of soil moisture. *Amer. Geophys. Union Trans.* 1948: 887-896.

- (89) WADLEIGH, C. H. 1946 The integrated soil moisture stress upon a root system in a large container of saline soil. *Soil Sci.* 61: 225-238.
- (90) WADSWORTH, H. A. 1934 Soil moisture and the sugar cane plant. *Hawaii. Planters' Rec.* 38: 111-119.
- (91) WADSWORTH, H. A. 1944 An interpretation of the moisture content-surface force curve for soils. *Soil Sci.* 58: 225-242.
- (92) WASHBURN, E. W., AND HEUSE, E. O. 1915 The measurement of vapor pressure lowering by air saturation method. *Jour. Amer. Chem. Soc.* 37: 309-321.
- (93) WHITNEY, M., GARDNER, F. D., AND BRIGGS, L. J. 1897 An electrical method of determining the moisture content of arable soils. *U. S. Dept. Agr. Div. Soils. Bul.* 6: 1-28.
- (94) WILSON, J. D., AND LIVINGSTON, B. E. 1932 Wilting and withering of grasses in greenhouse cultures as related to the water-supplying power of the soil. *Plant Physiol.* 7: 1-34.
- (95) WORK, R. A., AND LEWIS, M. R. 1936 The relation of soil moisture to pear tree wilting in a heavy clay soil. *Jour. Amer. Soc. Agron.* 28: 124-134.

METHODS OF MEASURING SOIL MOISTURE TENSION

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[Gardner and his co-workers (15) were among the first to relate the capillary potential function proposed by Buckingham (7) to measurements obtainable in moist soils with porous cups and vacuum gages. Kornev (30, 31, 32) and Joffe (22, 23) were early users of porous cups and manometers for measuring what they called the "absorbing power" and "suction force" of soils.) Shaw (70) correctly inferred from his experiments that the maximum mercury column rise obtainable with porous cups is determined by the properties of the apparatus and not by the colloid content of the soil, as some had assumed.

It is now generally accepted that over a certain range of soil moisture contents, water in a porous cup which is filled and connected to a manometer will come to pressure equilibrium with the soil. Likewise, the moisture content of a soil on a porous plate or membrane will attain a steady value if a constant pressure reduction is maintained across the plate or membrane. Early measurements (40) were converted to capillary potential values by dividing the pressure difference across the membrane by the density of water. This procedure, because of the reference conventions that were adopted, gave a negative value for the potential in unsaturated soils. The experimentally measured quantity, namely, the pressure difference across the porous wall or membrane, is usable directly for most applications of such data and has been variously termed *suction*, *pressure deficiency*, *capillary tension*, and *soil moisture tension*. This pressure difference is commonly expressed in standard atmospheres¹ or in terms of the length of a vertical water column which is equivalent to the pressure difference. Water column units are convenient to use for some cases because of the ease of conversion to hydraulic head values for flow studies (20, 51).

(Soil moisture tension is thus a physical property of water that, within limits, in moist soils can be directly measured or can be controlled in soil that is in contact with a porous membrane.) Since it is not known over what range of moisture contents water may be present in soil in "liquid" form, it should not be assumed that the water in the soil exists under a negative pressure equal to the pressure difference across the membrane. (The attraction of soil for water arises from force fields associated with interface boundaries in the soil-moisture system and so soil-moisture tension may be taken as a measure of this surface force action.)

Soluble salts in soils definitely affect the free energy and the availability of soil water to plants. Methods for measuring the free energy in the moisture range that will permit the growth of plants are not in a very satisfactory state at present. Consequently, this paper is concerned only with the component of the free energy that can be measured or controlled with porous cups and porous membranes.

¹ 1 atmosphere = 1.013×10^6 dyne cm.⁻² = 14.71 pounds in.⁻² = 76.39 cm. of mercury = 1036 cm. of water = 34.01 feet of water at 21°C.

TENSIOMETERS FOR MEASURING SOIL MOISTURE TENSION

(Numerous workers have contributed to the development of tensiometers (10, 15, 18, 19, 22, 23, 27, 40, 42, 43, 44, 45, 46, 67, 72), and various design arrangements have been used, depending on the materials available and the conditions under which measurements were to be made.) Design improvements will continue to be made as new materials become available. Some skill is required in the use of these instruments, but the design and construction have been brought to the stage where the units are fairly widely used for routine moisture measurements and conventional types are commercially available.

[For experimental work, the mercury manometer types are generally to be preferred because of the precision afforded. Units employing Bourdon spring vacuum gauges are not suitable for long-time outdoor use unless the gauge case is hermetically sealed, as is now done for commercial tensiometers. The precision afforded by Bourdon spring type vacuum gauges is ordinarily approximately ± 2 per cent of full range and is satisfactory for irrigation control work and some other applications.]

[Tensiometer readings are unreliable unless it is known that the unit is substantially filled with water. Otherwise the volume of water that must be displaced through the cup wall to attain equilibrium with the soil will be excessive. For this reason it is desirable for most installations to mount a transparent air-trap above ground and to make a connection to the cup in such manner that any air entering the system becomes visible in the airtrap (43, 52). Where necessary, tensiometer cups have been mounted at considerable distances from the vacuum gauge by using small-bore tubing for making the connection (10, 44). Provision must be made, however, for complete filling of the system with water and for checking to ensure that the unit remains substantially air-free.]

[The form, size, and arrangement of tensiometer parts can be varied considerably to suit individual requirements. Essential elements consist of a porous cup, a vacuum gauge, and a combined means for water filling and air removal.]

[The walls of the porous cup should be as permeable as possible and still have an air entry value greater than 1 atmosphere. That is, when the walls of the porous cup are saturated with water, the cup should withstand an air pressure difference of more than 15 pounds per square inch without leaking air.] Suitable cups can be made from ceramic clay by the drain-casting process, or cups can be purchased. [The size most commonly used for field work (44) was originally chosen so the cup could be inserted in the $1\frac{1}{4}$ -inch hole made by the standard Viehmeyer (73) soil sampling tube. Synthetic materials such as Koroseal (52) and Neoprene (10) are superior to rubber on tensiometer systems because they are less permeable to gases and less subject to change with age and exposure to light. Rubber tubing should not be used directly on copper because the formation of copper sulfide soon destroys the seal.]

Tensiometer readings are subject to a daily variation that has not yet been fully studied and explained. It may be due in part to change in moisture content of the soil because, for field installations, readings generally increase during the afternoon when the transpiration load is greatest. This diurnal swing is

greatest when the cup is near the soil surface and sometimes may be observed in absence of moisture extraction by plant roots. The effect of the diurnal fluctuation on the readings of field instruments can be minimized by making the readings at the same time of day, preferably in the morning, so as to follow a period of slow temperature change.

CONVERSION OF GAUGE READINGS

The following examples give methods for converting vacuum gauge readings to soil moisture tension values at the cup.

Case I. Procedure for setting the scale zero for a mercury manometer tensiometer when the mercury pot is rigidly coupled to the porous cup and the cup water is brought to zero tension by immersing the lower half of the cup in water. Vertical distances in centimeters are designated in figure 1A by the letters a, b, c, d . Let a designate the mercury column length when the cup water tension is made equal to zero by allowing the unit to come to equilibrium with a free water surface at the middle of the cup. Adding pressure increments through the system from the surface of the mercury in the pot to the midpoint of the cup gives the relation

$$13.5a + \Delta P - a - c - d = 0 \quad (1)$$

where ΔP represents the pressure change across the meniscus. Then, when the vessel of free water is removed and the cup water tension is T cm. of water, let us assume that the corresponding mercury column length is $\Delta a + a + b$ cm. Adding pressure increments around the system to the center of the cup gives

$$13.5(\Delta a + a + b) + \Delta P - b - a - c - d = T \quad (2)$$

Subtracting (1) from (2) gives

$$T = 13.5 \Delta a + 12.5b \quad (3)$$

where Δa is the lowering of the mercury surface in the pot corresponding to a column rise equal to b . If the pot diameter is 10 or more times the diameter of the mercury column, then Δa is less than 1 per cent of b and may be neglected. From (3) it is seen that, if the zero point of a scale which is graduated in centimeters is set at height a , the cup water tension in centimeters of water is simply $12.5 \times b$. Alternatively, it is convenient to use a special scale which is graduated in units of length equal to cm./12.5. Such a scale will give the cup water tension directly in centimeters of water if the scale zero is set at the level of the mercury column when the porous cup is half immersed in water.

Case II. Procedure for setting the scale zero for a mercury manometer tensiometer when the mercury pot is not fixed in elevation with respect to the cup or when the scale setting is to be checked after the cup is inserted in the soil. Referring to figure 1B, let e represent the column length when the tensiometer is filled with water, but with the airtrap stopper left out. Adding pressure increments through the system from the surface of the mercury in the pot to the airtrap opening gives

$$13.5e + \Delta P - e - c = 0 \quad (4)$$

Then, assuming the column length is $b + e + \Delta e$ when the cup tension is T cm. of water and adding pressure increments as before gives

$$13.5(\Delta e + e + b) + \Delta P - b - e - c - d = T \quad (5)$$

Subtracting (4) from (5) gives

$$13.5 \Delta e + 12.5 b - d = T \quad (6)$$

Neglecting Δe as before, it is apparent that T , in centimeters of water, is equal to 12.5 times the column reading on a scale which is graduated in centimeters and which has its zero set $(e + d/12.5)$ cm. above the surface of the mercury in the pot. Alternatively, a

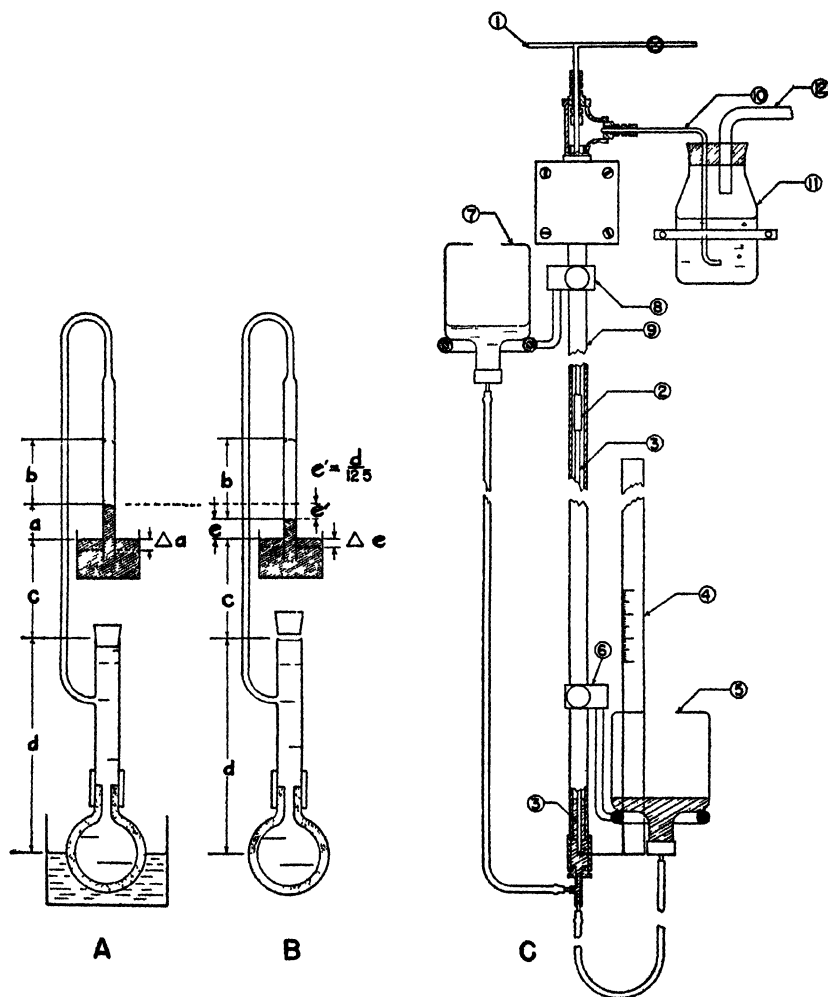


FIG. 1. A AND B. MANOMETER ARRANGEMENTS FOR CALCULATING SOIL MOISTURE TENSION AT THE POROUS CUP. C. PRESSURE CONTROL TOWER

special scale like that mentioned above, and with its zero at $(e + d/12.5)$ cm. would read directly the cup water tension in centimeters of water. In other words, referring to the scale zero correction in Case I, we have

$$a = e + e' = e + \frac{d}{12.5} \quad (7)$$

Case III. Bourdon spring vacuum gauges are calibrated at the factory to read vacuum pressure at the gauge. Consequently the cup water tension may be obtained from the gauge reading by subtracting the pressure which is equivalent to the vertical component of the intervening water column.

OPERATING CHARACTERISTICS OF TENSIOMETERS

The essential operating characteristics of tensiometers can be specified in terms of the characteristics of the cup and gauge. The following list includes some of these characteristics, along with methods for measurement:

1. The entry value, which is the most critical property of the porous cup, is the air pressure difference required to cause an air leak when the cup wall is saturated with water. The cups to be tested should be saturated with water by wetting under vacuum or by unidirectional flow through the cup wall. This latter can be done by carefully filling the cup while keeping the outside dry, or alternatively, by immersing the *outside* of the cup in water. Wetting the wall from both sides leaves a layer of compressed air in the midsection which will bubble out from the larger pores and confuse the measurement. Empty a thoroughly wetted cup and connect to a compressed air source through a pressure regulating valve. Immerse the cup and slowly raise the air pressure. The entry value is the minimum pressure at which bubbling begins through the cup wall. Ordinarily this should be greater than 1 atmosphere.

2. Cup area can be estimated from the linear dimensions of the cup surface which makes contact with the soil. Considerations determining the shape and area of the cup are: (a) amount of soil space available, (b) amount of soil removal and disturbance permissible, (c) need for determining a tension reading characteristic of a localized place rather than an average value for a larger surface, (d) convenience of installation.

3. Cup conductance, K , has been defined (44) as the volume of water passing through the cup wall per unit of time per unit of pressure difference². The measurement is made with both sides of the wall in contact with free water. Cup conductance should be as high as possible and still satisfy condition 1 above. Cup conductance values have ranged from 0.1 to 10 cc. minute⁻¹ atmospheres⁻¹ for tensiometer cups used by the writer.

4. Vacuum gauge accuracy involves such factors as accidental errors in reading the scale, malfunction of the gauge due to friction or a fouled meniscus, as well as precision of calibration of the scale. Gauge accuracy is ordinarily given as the maximum error of readings over the whole range, expressed as percentage of full scale reading. As previously mentioned, the accuracy of ordinary Bourdon spring gauges is approximately ± 2 per cent. Mercury manometers can be considerably more accurate than this, depending on the care

² Cup conductance can be simply measured with mercury column tensiometers because the pressure difference and the rate of passage of water through the porous wall are directly related to the manometer reading. By this method (44) it turns out that at 20°C. the cup conductance, K_{20} , is given by the expression

$$K_{20} = \frac{57 \times A}{t}, \text{ cc. min.}^{-1} \text{ atmos.}^{-1} \quad (8)$$

where A is the cross-sectional area of the mercury column in cm.² and t is the time in minutes for the mercury column height to decrease by 50 per cent after immersion of the cup in water. If the measurement is made at a temperature, T , appreciably different from 20°C., the effect of this temperature shift can be corrected by using the expression

$$K_{20} = \frac{57 \times A}{t} \times \frac{\eta T}{\eta_{20}} \quad (9)$$

where η_T and η_{20} are respectively the viscosity of water at T and 20°C.

in making scale zero settings and care in avoiding capillary depression errors at the mercury meniscus. In connection with this latter point, a mercury column used for calibration work should have a larger diameter than that which is feasible on mercury-column tensiometers.

5. Gauge sensitivity. Vacuum gauges used on tensiometers require liquid transfer to or from the gauge to change the gauge reading. The change in gauge reading per unit volume change has been defined as the gauge sensitivity (42), S , and may be expressed in atmospheres per cubic centimeter. The sensitivity for a mercury manometer with a bore of 1.5 mm. is 0.6 atmosphere/cc. The sensitivity for 2-inch Bourdon spring vacuum gauges is approximately 0.8 atmosphere/cc.

6. The response time-constant for a tensiometer is $1/KS$ and is a measure of the over-all responsiveness of the instrument to a change of soil moisture tension at the cup surface. For example, if a tensiometer is *completely* filled with water and evaporation from the porous cup has brought the gauge to a reading of T_0 atmospheres, then the gauge reading after submergence of the cup in water is given by the expression³

$$T = T_0 e^{-KS t} \quad (10)$$

where t is the time of submergence in minutes. It is seen that when $t = 1/KS$, $T = T_0/e = T_0/2.718$ or T is reduced to 63.2 per cent of its initial value, T_0 . Designating this time for the 63.2 per cent change as the "time-constant" is in harmony with other measurements which follow the exponential law, especially in heat and electricity. The response time-constant for tensiometers designed for field use is usually about 1 minute. }

✓ RANGE OF USEFULNESS OF TENSIOETERS

[Tensiometers have been used for measuring soil moisture under field (1, 2, 4, 6, 12, 16, 18, 24, 25, 26, 27, 28, 29, 36, 42, 44, 46, 50, 59, 62, 64, 65, 72, 74, 78), greenhouse (38, 45, 72, 75, 79), and laboratory (41, 61, 63, 67) conditions. The tension range covered by tensiometers extends from 0 to about 850 cm. of water, or about 0.85 atmosphere. This is only a small fraction of tension range over which soil moisture is available for plant growth, since the wilting percentage corresponds approximately to the 15-atmosphere-percentage. When the soil moisture tension at the porous cup exceeds 0.85 atmosphere, water is extracted from the tensiometer and the gauge readings become unreliable.]

[The limitation of the useful range of tensiometers appears less severe when stated in terms of the available moisture content range of the soil. Insufficient data are at hand for any broad generalization, but experience tends to confirm

³ In accordance with the definition in paragraph 3 above, the cup conductance, K , is defined by the relation

$$dQ/dt = -KT \quad (11)$$

where dQ/dt is the number of cubic centimeters of water per minute passing through a tensiometer cup which is submerged in water and T is the gauge reading in atmospheres. Further, in accordance with paragraph 5 above, the gauge sensitivity, S , is defined by the relation

$$S = dT/dQ \quad (12)$$

solving equation (12) for dQ , substituting in equation (11) and rearranging gives

$$\frac{dT}{T} = -KS dt \quad (13)$$

After integration and change to the exponential form, this becomes equation (10).

the earlier tentative conclusion (56) that in the finest textured soils the tension range of 0 to 0.85 atmosphere covers about half of the moisture content range between field capacity and the wilting percentage. For the coarser sandy soils the tensiometer may cover more than 90 per cent of the available moisture content range. Stoeckler and Aamodt (72), for example, found that "when the mercury depression exceeds 35 cm., the moisture content for the loamy sand soils is at or within a few per cent of the wilting coefficient; watering will thus be necessary soon after this pull is attained." Similar conditions were found by Kelley *et al.* (26) for Coachella loamy sand.

Tensiometers have a unique advantage over other moisture-measuring devices now available in that they measure a property of soil water which is directly related to the work plants must do against surface force action to extract water from the soil (75, 76, 77). Consequently, for some purposes, the calibration of tensiometer readings against soil moisture content is unnecessary.

Kelley *et al.* (26) recently presented a comparison of measurements and characteristics of several types of moisture meters. They also gave an excellent discussion of conditions that are encountered in the field in any attempt to measure and control soil moisture.

A discussion of tensiometer response at field capacity is deferred to a later section of this paper.

RELATION OF MOISTURE TENSION TO SOIL MOISTURE CONTENT

Porous cells and porous membranes provide the most convenient means for measuring the relation between soil moisture tension and moisture content in the plant-growth moisture range. Centrifugation methods employing a controlled outflow boundary condition (14, 63, 64) have been successfully used for this purpose, but the method is not well suited for routine use. Cryoscopic methods have been used, but there are certain difficulties in the interpretation of the cryoscopic data that have not yet been resolved.

Curves showing the relation between moisture content and soil moisture tension have been referred to as sorption curves (64), characteristic curves (8), and retention curves (47). Schofield (67) proposed a logarithmic scale, which he called the pF , and which has been considerably used. Moisture relations during removal of moisture from soil are of chief interest from practical agricultural consideration because, in the field, infiltration processes are usually of shorter duration than soil moisture removal processes. Haines (17) studied and described hysteresis effects for porous media, and this phenomenon has been observed and measured in soils (41, 47, 53, 60, 69). In view of the hysteresis effect, perhaps the expression selected for designating the curve should indicate the direction of the measuring process, that is, sorption vs. desorption; uptake vs. retention. Retention may overstress the static idea. Perhaps uptake and release would make a better combination, *retention* being reserved as a neutral term for covering both processes. The term *sorption* has been misused in connection with soil moisture curves because the word is derived from the Latin *sorbere*, meaning to suck in, whereas *sorption* has been more often applied to moisture-release data,

for which it would have been better to use the term *desorption*. The terms *moisture characteristic* or *characteristic curve* are good. Absence of a directional feature may be considered both as an advantage and as a disadvantage.

As a student in the laboratory of Willard Gardner in 1925, the writer assisted with experiments that involved the placement of a porous-cup-manometer combination in a can of soil that could be weighed from time to time for obtaining moisture-retention data. This method has been used by various workers since that time (18, 36, 69, 72). An alternate method is to take moisture samples adjacent to a tensiometer in the field (64, 74). By far the more common method for obtaining moisture retention data is to control the soil moisture tension and allow the soil moisture content to come to a steady value by transfer through a porous wall. Special cells have been constructed for this type of work (40, 47, 50, 55, 56). Porous ceramic cells and plates are well suited for measurements in the 1-atmosphere tension range.

The relation of moisture uptake and release processes to pore-size distribution and structure in soils has directed considerable attention to measurements in the low tension range. For this purpose, suction units making use of filter paper (3, 9, 17, 67), blotting paper (34, 35) and sintered glass funnels (5, 13, 66) have been used, and such measurements give very useful information on soil structure (21, 33).

Suction apparatus, like the tensiometer, is necessarily limited to moisture tension values of less than 1 atmosphere. Schofield (67) mentioned the possibility of using air pressure to attain higher tension values. S. J. Richards (60) used specially cast ceramic pressure cells for this purpose. The pressure plate apparatus described by Richards and Fireman (55) has, over a period of years, proved to be very satisfactory for measuring moisture uptake and release by soils. The gasket seal for the porous plate has been trouble-free, as has also been the water-tower pressure control system they described. If the desired measurements extend over a considerable period, some precaution must be taken to prevent evaporation from the burettes. No apparatus correction is necessary, because over the 1-atmosphere range the water released by the porous plate and mounting is negligible.

During the last few years many thousands of single moisture-retention values have been made in this country to appraise field capacity, which becomes a critical factor in the classification of sandy soils. Porous plate apparatus suitable for making measurements on large numbers of samples has recently been described (58) along with a mercury tower for air-pressure control. Continued work with mercury-tower systems has led to the unit shown in figure 1C. The earlier model of mercury-tower control worked quite satisfactorily, but in building subsequent units it was found that the porosity and permeability of the porous disc were rather critical. If the pores of the disc are too large, mercury leaks through, and if the permeability is too low, the control pressure depends somewhat on the bubbling rate. In the unit here described, the porous disc is eliminated, the water and mercury towers are combined in the same unit, and the leveling bulbs are used both for controlling and measuring the pressure.

The needle valve at the top of the diagram is slightly opened to admit a slow flow of air from a compressed air source to the soil chamber, 1, and the control tower acts like a pressure release valve. Air enters the tower through the $\frac{1}{2}$ -inch copper tube which is joined to a glass tube by the Koroseal sleeve, 2. The lower end of the glass tube, 3, which has a bore of approximately 3 mm., is cut at an angle and forms the bubbler tip. The bottle, 5, is open at the top to atmospheric pressure, and the mercury height can be adjusted on the scale, 4, by the clamp, 6. The control pressure can be read directly on the scale, once the scale zero is set at the level of the bubbler tip. This is done by comparison with another manometer, which can be temporarily attached to the system. To obtain low pressures, the clamp, 6, is lowered against the pipe coupling and the water bulb, 7, is rotated around in front of the scale and adjusted to give the desired water column height. The waste air from the bubbler tip returns through the pipe, 9, and the $\frac{1}{2}$ -inch tube, 10, to the bottle, 11, which serves as a bubbling rate indicator. The possibility of harmful concentrations of mercury vapor in the laboratory can be avoided by use of a waste line, such as shown at 12. It is best to keep a layer of water on top of the mercury whenever bubbling is taking place in mercury. This does not disturb the accuracy of the pressure reading on the leveling bulb scale. The control pressure cannot be reduced below the back pressure arising in bottle 11. The inflow and outflow lines, 1 and 10, must be kept reasonably large, otherwise friction loss will make the control pressure somewhat dependent on bubbling rate. The metal fittings which are in contact with the mercury should be iron. The black iron pipe, 9, is $4\frac{1}{2}$ feet long and is $\frac{1}{2}$ -inch pipe size.

PRESSURE MEMBRANE APPARATUS

To obtain moisture tension control beyond the limit of ceramic plates, Woodruff (79) and Richards (48, 49) independently used pressure membrane apparatus which is somewhat similar in construction to ultrafiltration equipment. Improvements in the construction of pressure membrane apparatus, along with suggestions on pressure controls, have recently been published (57).¹ Trouble may be experienced with gaskets until some skill is acquired in closing the chamber. A calibrated torque wrench is very convenient for training new operators. Gasket rubbers of two grades of hardness have given repeated leak-free service; the gasket problem, therefore, is believed to be largely a matter of keeping the gasket surfaces clean and learning how tight to secure the lid bolts to prevent leaks and still avoid spoiling the gasket.

Detailed suggestions for the operation and use of pressure membrane apparatus given elsewhere (39, 57) will not be repeated here.² The following additional suggestions may prove helpful:

Occasional trouble has been experienced with the membrane's pulling up and disturbing the soil samples when the cell is opened. This can be avoided by attaching to the lower plate (57) two turn buttons or excentric-headed screws which can be rotated to engage horizontal slots in opposite sides of the cylinder wall.

The pressure membrane apparatus itself has a moisture change with pressure change that must be taken into account for certain types of use, such as when the moisture release curve for a single sample in the cell is calculated from successive outflow volumes, corresponding to successive pressure increments. It has been found that 4 to 8 ml. of water may be given up by the membrane and the underlying screen base in going from equilibrium at 1 atmosphere to equilibrium at 15 atmospheres. This characteristic apparently depends on the type of support given to the membrane by the screen, and also on the moisture properties of the membrane.

Air pressure systems for pressure membrane apparatus have already been described³

(57), but a safety feature which has been added by L. V. Wilcox of the Rubidoux Laboratory is, with his permission, here passed along to pressure-membrane users. In normal use, membrane cells require a very small volume of air, so it is not economical to provide high-pressure pumping systems that are rated for continuous service. Membranes sometimes fail in use and should this occur at night the pressure-limit switch would throw the compressor into continuous operation. To prevent this, Wilcox introduced a time switch in the compressor motor line, in series with the pressure-limit switch. The time switch is set to close for 5 minutes out of each hour. This will supply any normal air requirement and yet prevent overtime operation of the compressor.

Pressure membrane apparatus is now commercially available and is in use in a number of soil research laboratories.

MOISTURE RETENTION CURVES

Figure 2⁴ shows a moisture release curve for Chino clay, an agricultural soil from Orange County, California. Data for the 1-atmosphere range were obtained with pressure plate apparatus (55); those from 1 to 15 atmospheres, with

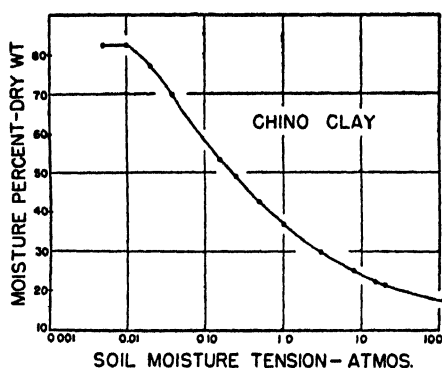


FIG. 2. MOISTURE RELEASE CURVE FOR CHINO CLAY AS OBTAINED ON POROUS MEMBRANES

the 12-inch pressure membrane units (48); and those at the higher pressures, in a specially constructed 4-inch cell. Visking sausage casing was used as the membrane. This material, over a period of years, has proved to be of uniform high quality, well suited for this special use, and has been employed at membrane pressures up to 180 atmospheres. Extensive work at high pressures has not been done, but results thus far seem to indicate that leaks through the membrane often develop at pressures above 110 atmospheres. The independent variable, which for this case was soil moisture tension, has been plotted on the horizontal axis. The logarithmic scale is used to compress the range. This may or may not be desirable. For some purposes, especially when moisture availability to plants is considered, it seems preferable to use the linear scale for plotting.

Figure 3 gives moisture release curves for five soils over the entire moisture tension range that will permit growth of crops. Even for the finer-textured soils

⁴ The curves in figures 2, 3, and 4 were obtained during 1941 with the assistance of L. R. Weaver on a project that has been partly reported (57).

not much available water remains after a tension of 3 to 5 atmospheres is attained. This fact is illustrated in another way by the method of plotting used for the same data in figure 4. The data are shown on a linear scale to 0.85 atmosphere, after which the scale is broken and a straight line is drawn sloping down to the 15-atmosphere-percentage.

The moisture release data for the curves in figures 2, 3, and 4 were obtained on samples that had been air-dried and passed through a 2-mm. sieve. The samples were then placed on the porous plate or membrane, were thoroughly wetted, and were brought successively to the indicated tensions. The data thus relate to soil conditions after cultivation. The curves would be appreciably different in

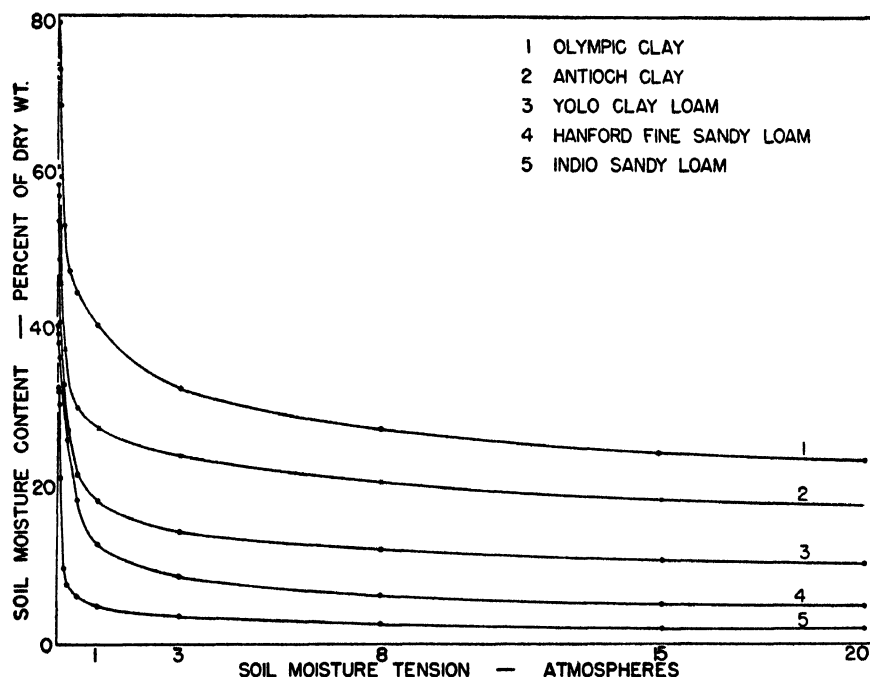


FIG. 3. MOISTURE RELEASE CURVES FOR FIVE SOILS OVER 0 TO 20-ATMOSPHERE TENSION RANGE

the low tension range if the measurements had been made on samples having undisturbed field structure. Such samples can be conveniently obtained with the Lutz sampler (35), with which the sample is retained in a moisture box. When ready for test, the lid is replaced by a thin cloth retainer, and after being wetted, the boxes are placed in a tissue-paper pad on the porous plate (58) for obtaining the moisture release data. One advantage of the pressure-type apparatus lies in the fact that by attaching a burette to the outflow, information can be obtained conveniently regarding the attainment of equilibrium without the disturbance that is caused by successive weighings during approach to equilibrium.

Pore-size distribution data as calculated from moisture release curves on un-

disturbed structure samples can be obtained on samples 5 or more cm. high in reasonable time because $\frac{1}{2}$ atmosphere, or at most 1 atmosphere, of tension covers the range of principal interest. At higher tensions with the pressure membrane apparatus it has been found expedient for equilibrium studies to restrict the sample height to 1 cm. or less. Occasional soils have been found for which several days have been required to attain equilibrium at 15 atmospheres with a sample height of only 2 mm.

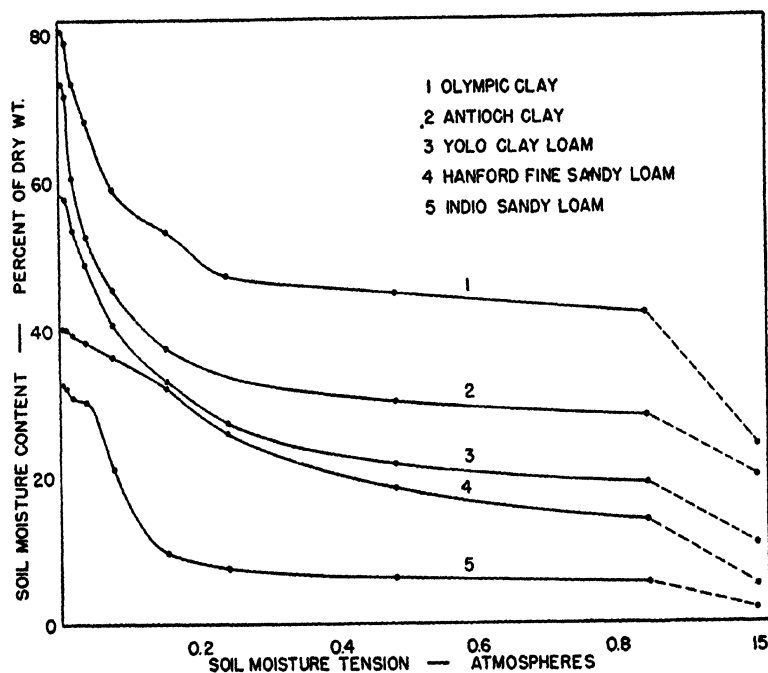


FIG. 4. MOISTURE RELEASE DATA TAKEN FROM THE CURVES IN FIGURE 3 BUT PLOTTED TO A DIFFERENT SCALE

FIELD CAPACITY

Richards and Weaver (56) defined the $\frac{1}{2}$ -atmosphere percentage as the percentage of moisture in a sample of soil subjected to the following treatment: (a) air-drying, (b) passage through a 2-mm. round-hole sieve, (c) wetting for at least 6 hours with an excess of water on a porous plate, (d) bringing to equilibrium at $\frac{1}{2}$ -atmosphere tension. Care is required to make sure replicate subsamples are similar in texture and represent the main sample. The $\frac{1}{2}$ -atmosphere percentage was found to correlate roughly with the moisture equivalent, which has been considerably used as an index of field capacity. Colman (11) found with a group of forest soils that the $\frac{1}{2}$ -atmosphere percentage (like moisture equivalent) is appreciably lower than field capacity in coarse soils, is equal to field capacity at

ture values around 20, and is somewhat higher than field capacity in finer-textured soils.

Results from a number of years' experience in the West with tensiometers in a variety of soils in the field indicate that under conditions ordinarily designated as field capacity, tensiometer readings usually lie in the range from 30 to 150 cm. of water. Smith and Browning (71), working in the Midwest, have reported a slightly lower range, of 25 to 125 cm. of water. In some sandy soils the tensiometer reads 100 cm. of water at field capacity, and the 100-cm. moisture retention value as determined on a porous plate agrees very well with the field capacity value.

On the other hand, from the correspondence between the $\frac{1}{3}$ -atmosphere percentage and the moisture equivalent, one might expect, at least for medium- and fine-textured soils, that tensiometer readings would be near 345 cm. of water at field capacity. The reasons for this discrepancy are not definitely known. Structure may be a factor, because moisture release curves for sieved and field-structure samples usually differ appreciably. Hysteresis and the degree of wetting may also play a part. The screened sample on the porous plate is very likely more thoroughly saturated with water than is soil in the field. The observations of Smith and Browning (71) support this view.

The hydraulics of "field capacity" are not well understood at present. The relation of moisture equivalent or some moisture retention value to field capacity may have practical usefulness, but certainly we do not yet appear to have a satisfactory laboratory procedure for determining field capacity for all soils. The writer believes that the change of unsaturated permeability with moisture content may be an important factor in determining when downward drainage becomes negligible. We can measure the permeability of a sample, but we cannot extract from the sample information on the magnitude of the hydraulic gradient which acts in the soil in the field, because this is a characteristic of the whole profile. Because of its practical importance to agriculture, we should continue to search for better means for estimating field capacity. We must not neglect the probability, however, that some soils simply do not have a field capacity, as the term is ordinarily defined: that is, for some soils, there does not appear to be a definite moisture content at which moisture movement becomes negligible.

SOIL MOISTURE TENSION AND WILTING PERCENTAGE

Because of lack of good measurements, the energetics of soil moisture at the wilting percentage are not well understood. Vapor pressure measurements do not yet have sufficient precision, and so far as the writer is aware, no data have been published on the freezing point of water in soil in which plants have wilted. Freezing points on soil samples made up to the wilting percentage may be subject to some question as to reliability for precise interpretation. The standard deviation for the determination of the permanent wilting percentage with plants is small for trained observers, but even so, when applied to curves such as those in figure 3 this deviation corresponds to a considerable range in soil moisture tension.

Though this rapid change in tension with moisture causes difficulties in determining the tension at wilting, it apparently makes possible a reasonably reliable physical method for estimating the lower limit for available moisture in soils. Richards and Weaver (54, 56) found that the wilting percentages for a number of western soils is near or slightly higher than the 15-atmosphere percentage. Peele, Beale, and Lesene (37) found a similar relation for a group of South Carolina soils. Further experience is required to determine how widely this relation holds. Unpublished data for a considerable number of soils have come to the writer's attention, and all of the results have been consistent with the published data with the exception of a single lot of samples. As the wilting points for this lot of samples could not be duplicated, the lot was not considered to be a valid exception. The possibility that the wilting points for some types of soils may deviate considerably from the 15-atmosphere percentage should not, however, be overlooked. This would be expected, for example, in saline soils where plant-soil-water relations may be considerably altered.

Equilibrium determinations on porous membranes are related to a definite physical condition of the soil moisture, and as such, the determination is independent of the apparatus and method, provided the state of the soil remains the same. [For example, Peele and co-workers used a much thinner layer of soil than did Richards and Weaver and yet obtained similar results.]

There is evidence that ordinary handling processes like air-drying and crumbling have little effect on the 15-atmosphere percentage, provided the sample is allowed to remain wet long enough before the extraction is started. Because the measurement is very sensitive to texture change, the most difficult step in making 15-atmosphere determinations is to obtain subsamples having representative texture. The difference between taking subsamples with a spoon or a spatula may be great because the large particles tend to roll off from a spatula. The following procedure is suggested for this method:

Use an approximately 25-gm. sample and rubber rings approximately 1 cm. high and 5 cm. in diameter (can be cut from tire inner tubing) to contain the sample on the membrane.

Pass the soil through a 2-mm round-hole sieve, using a rubber pestle if necessary. "Pull" the whole sample on a plastic coated cloth in such a manner as to *produce mixing and not segregation of the aggregate sizes*. Use a thin spoon or scoop to remove small portions of the soil from different sections of the soil layer on the cloth. In this manner, collect in moisture boxes the right amount of soil for individual determinations. Make determinations in duplicate. Dump the soil samples into the rubber retaining rings on the Visking membrane, level the soil, cover each sample with a square of waxed paper, and allow the samples to stand at least 16 hours with an excess of water on the membrane.

After the wetting period, remove excess water from the membrane with a pipette or syringe, close the cell and admit air to the soil chamber at a pressure of 15 atmospheres (220 pounds inch⁻²).

After a few hours there is a marked decrease in the rate at which moisture is extracted from the soil, the outflow rate then being limited mainly by the low soil permeability for unsaturated flow rather than the low membrane permeability. The soil samples then have sufficient rigidity to resist plastic flow and compaction when a 4 pound inch⁻² pressure differential is applied to the rubber diaphragm at the top of the cell. This diaphragm action holds the sample firmly in contact with the membrane and considerably hastens moisture extraction for fine-textured soils, which exhibit appreciable shrinkage. The diaphragm is unnecessary for medium and coarse-textured soils.

Remove the samples any time after 48 hours (for samples 1 cm. high) after start of the extraction, or when readings on an outflow burette indicate equilibrium is attained. Some soils will come to equilibrium in 18 to 20 hours. Avoid undesired changes in the moisture content by transferring the samples to moisture boxes as soon as possible after releasing the extraction pressure. Determine the moisture content by drying to constant weight at 105°C. Express results as percentage moisture, dry-weight basis.

SUMMARY

The soil moisture tensiometer, which consists of the combination of a porous cup and a vacuum gauge, can be used for measuring soil moisture tension values up to about 0.85 atmosphere. References are given for a number of papers dealing with the development and construction of tensiometers and reporting the experience of various workers with tensiometers under field conditions.

References are also cited which relate to the use of porous clay and cellulose membrane apparatus for measuring the uptake and release of moisture by soils at various moisture tension values. Typical moisture retention curves for a number of soils are given at soil moisture tension values up to 100 atmospheres. Methods for making moisture retention measurements at known soil moisture tension are reviewed, and the relation of such measurements to the field moisture properties of soils is briefly discussed.

REFERENCES

- (1) ANDERSON, E. M. 1946 Tipburn of lettuce. Effect of maturity, air and soil temperature, and soil moisture tension. *N. Y. (Cornell) Agr. Exp. Sta. Bul.* 829: 1-14.
- (2) ALLMAN, M. S., AND KHONKE, H. 1948 The pF of soil moisture at the wet limit of the plowing range. *Soil Sci. Soc. Amer. Proc.* (1947) 12: 22-23.
- (3) BOUYOUCOS, G. J. 1929 A new, simple and rapid method for determining the moisture equivalent of soils, and the role of soil colloids on this moisture equivalent. *Soil Sci.* 27: 233-240.
- (4) BOYNTON, D. 1939 Capillary tension as a measure of the pore space unoccupied by water in some dense orchard soils. *Soil Sci.* 47: 347-352.
- (5) BRADFIELD, R., AND JAMISON, V. E. 1939 Soil structure—attempts at its quantitative characterization. *Soil Sci. Soc. Amer. Proc.* (1938) 3: 70-76.
- (6) BROWNING, G. M., AND MILAM, F. M. 1941 The lateral movement of water in relation to contour furrows. *Soil Sci. Soc. Amer. Proc.* (1940) 5: 386-389.
- (7) BUCKINGHAM, E. 1907 Studies on the movement of soil moisture. U. S. Dept. Agr. Bur. Soils Bul. 38.
- (8) CHILDS, E. C. 1940 Use of soil moisture characteristics in soil studies. *Soil Sci.* 50: 239-252.
- (9) CHILDS, E. C. 1942 Stability of clay soils. *Soil Sci.* 53: 79-92.
- (10) COLMAN, E. A., HANAWALT, W. B., AND BURCK, C. R. 1946 Some improvements in tensiometer design. *Jour. Amer. Soc. Agron.* 38: 455-458.
- (11) COLMAN, E. A. 1947 A laboratory procedure for determining the field capacity of soils. *Soil Sci.* 63: 277-283.
- (12) CUMMINGS, R. W., AND CHANDLER, R. F. JR. 1941 A field comparison of the electrothermal and gypsum block electrical resistance methods with the tensiometer method for estimating soil moisture *in situ*. *Soil Sci. Soc. Amer. Proc.* (1940) 5: 80-85.
- (13) DONAT, J. 1937 Ein Verfahren zur Kennzeichnung des Bodengefüges. *Ernäh. Pflanze* 33(235): 357-360.
- (14) GARDNER, R. 1937 A method of measuring the capillary tension of soil moisture over a wide moisture range. *Soil Sci.* 43: 277-283.

- (15) GARDNER, W., ET AL. 1922 The capillary potential function and its relation to irrigation practice. *Phys. Rev.* 20: 196.
- (16) HAINES, W. B. 1927 Studies in the physical properties of soils: IV. *Jour. Agr. Sci.* 17: 264-290.
- (17) HAINES, W. B. 1930 Studies in the physical properties of soils: V. *Jour. Agr. Sci.* 20: 97-116.
- (18) HECK, A. F. 1934 A soil hygrometer for irrigated cane lands of Hawaii. *Jour. Amer. Soc. Agron.* 26: 274-278.
- (19) HUNTER, A. S., AND KELLEY, O. J. 1946 Changes in the construction of soil moisture tensiometers for field use. *Soil Sci.* 61: 215-218.
- (20) ISRAELSEN, O. W., AND McLAUGHLIN, W. W. 1932 Drainage of land overlying an artesian groundwater reservoir. *Utah Agr. Exp. Sta. Bul.* 242.
- (21) JAMISON, V. C. 1942 Structure of a Dunkirk silty clay loam in relation to pF measurements. *Jour. Amer. Soc. Agron.* 34: 307-321.
- (22) JOFFE, J. S., AND McLEAN, H. C. 1925 Suction force of soils. *Science* 62: 548.
- (23) JOFFE, J. S. 1925 Colloidal behavior of soils and soil fertility: I. *Soil Sci.* 20: 169-174.
- (24) KELLEY, A. P. 1927 The suction force of soils and its demonstration in the plant habitat. *First Internatl. Cong. Soil Sci. Proc.* 1: 535-538.
- (25) KELLEY, O. J., HUNTER, A. S., AND HOBBS, C. H. 1945 The effect of moisture stress on nursery-grown guayule with respect to the amount and type of growth and growth response on transplanting. *Jour. Amer. Soc. Agron.* 37: 194-216.
- (26) KELLEY, O. J., ET AL. 1946 A comparison of methods of measuring soil moisture under field conditions. *Jour. Amer. Soc. Agron.* 38: 759-784.
- (27) KENWORTHY, A. L. 1945 Cup conductance, field and laboratory calibration of tensiometers employing inexpensive porous cups. *Soil Sci.* 59: 397.
- (28) KNOBLAUCH, H. C., RICHARDS, S. J., AND LINT, H. C. 1940 Soil moisture tension under various conservation practices. *Soil Sci. Soc. Amer. Proc.* (1939) 4: 433-437.
- (29) KNOBLAUCH, H. C., LINT, H. C., AND RICHARDS, S. J. 1942 Soil moisture tension under various conservation practices: II. *Soil Sci. Soc. Amer. Proc.* (1941) 6: 480-483.
- (30) KORNEV, B. G. 1923 The suction force of soils. *Zhur. Opytn. Agron.* (Russian) 22: 105-111.
- (31) KORNEV, B. G. 1926 La capacité d'absorption du sol, appareils pour la mesurer—arrosage automatique. *Ann. Sci. Agron.* 43: 353-385.
- (32) KORNEV, B. G. 1924 The absorbing power of soils and the principle of automatic self-irrigation of soils. (Abstract in *Soil Sci.* 17: 428-429.)
- (33) LEAMER, R. W., AND LUTZ, J. F. 1940 Determination of pore-size distribution in soils. *Soil Sci.* 49: 347-360.
- (34) LEAMER, R. W., AND SHAW, B. 1941 A simple apparatus for measuring noncapillary porosity on an extensive scale. *Jour. Amer. Soc. Agron.* 33: 1003-1008.
- (35) LUTZ, J. F., ET AL. 1947 Effects of cover crops on pore-size distribution in a coarse plain soil. *Soil Sci. Soc. Amer. Proc.* (1946) 11: 43-46.
- (36) NEAL, O. R., RICHARDS, L. A., AND RUSSELL, M. B. 1938 Observations on moisture conditions in lysimeters. *Soil Sci. Soc. Amer. Proc.* (1937) 2: 35-44.
- (37) PEELE, T. C., BEALE, O. W., AND LESENE, F. F. 1948 Irrigation requirements of South Carolina soils. *Agr. Engin.* 29: 157-159.
- (38) POST, K., AND SEELEY, J. G. 1943 Automatic watering of greenhouse crops. *N. Y. (Cornell) Agr. Exp. Sta. Bul.* 793: 1-26.
- (39) REITEMEIER, R. F., AND RICHARDS, L. A. 1944 The reliability of the pressure membrane method for extraction of soil solution. *Soil Sci.* 57: 140-145.
- (40) RICHARDS, L. A. 1928 The usefulness of capillary potential to soil moisture and plant investigators. *Jour. Agr. Res.* 37: 719-742.

- (41) RICHARDS, L. A. 1931 Capillary conduction of liquids through porous mediums. *Physics* 1: 318-333.
- (42) RICHARDS, L. A., AND NEAL, O. R. 1937 Some field observations with tensiometers. *Soil Sci. Soc. Amer. Proc.* (1936) 1: 71-91.
- (43) RICHARDS, L. A., AND GARDNER, W. 1936 Tensiometers for measuring the capillary tension of soil water. *Jour. Amer. Soc. Agron.* 28: 352-358.
- (44) RICHARDS, L. A., RUSSELL, M. B., AND NEAL, O. R. 1938 Further developments on apparatus for field moisture studies. *Soil Sci. Soc. Amer. Proc.* (1937) 2: 55-64.
- (45) RICHARDS, L. A., AND PEARSON, R. W. 1939 A soil moisture tensiometer with a compact manometer. *Jour. Amer. Soc. Agron.* 31: 986-989.
- (46) RICHARDS, L. A., NEAL, O. R., AND RUSSELL, M. B. 1940 Observations on moisture conditions in lysimeters: II. *Soil Sci. Soc. Amer. Proc.* (1939) 4: 55-59.
- (47) RICHARDS, L. A. 1941 Uptake and retention of moisture by soils as related to distance to a water table. *Jour. Amer. Soc. Agron.* 33: 778-786.
- (48) RICHARDS, L. A. 1941 A pressure membrane extraction apparatus for soil solution. *Soil Sci.* 51: 377-386.
- (49) RICHARDS, L. A. 1944 U. S. Patent 2353260. Dedicated to the free use of the people in the territory of the United States.
- (50) RICHARDS, L. A., AND HUBERTY, M. R. 1941 Moisture studies under citrus using tensiometers. *Proc. Amer. Soc. Hort. Sci.* 39: 73-79.
- (51) RICHARDS, L. A. 1941 Hydraulics of water in unsaturated soil. *Agr. Engin.* 22: 325-326.
- (52) RICHARDS, L. A. 1942 Soil moisture tensiometer materials and construction. *Soil Sci.* 53: 241-248.
- (53) RICHARDS, L. A., AND WEAVER, L. R. 1943 The sorption block soil moisture meter and hysteresis effects related to its operation. *Jour. Amer. Soc. Agron.* 35: 1002-1011.
- (54) RICHARDS, L. A., AND WEAVER, L. R. 1943 Fifteen atmosphere percentage as related to the permanent wilting percentage. *Soil Sci.* 56: 331-339.
- (55) RICHARDS, L. A., AND FIREMAN, M. 1943 Pressure-plate apparatus for studying moisture sorption and transmission by soil. *Soil Sci.* 56: 395-404.
- (56) RICHARDS, L. A., AND WEAVER, L. R. 1944 Moisture retention by some irrigated soils as related to soil moisture tension. *Jour. Agr. Res.* 69: 215-235.
- (57) RICHARDS, L. A. 1947 Pressure membrane apparatus construction and use. *Agr. Engin.* 28: 451-454, 460.
- (58) RICHARDS, L. A. 1948 Porous plate apparatus for measuring moisture retention and transmission by soil. *Soil Sci.* 66: 105-110.
- (59) RICHARDS, S. J., AND LAMB, J. 1937 Field measurements of capillary tension. *Jour. Amer. Soc. Agron.* 29: 772-780.
- (60) RICHARDS, S. J. 1940 Soil moisture content calculations from capillary tension records. *Soil Sci. Soc. Amer. Proc.* (1939) 3: 57-64.
- (61) RICHARDS, S. J., AND JOFFE, J. S. 1940 Percolation and sorption of water as they relate to infiltration in collington sandy loam. *Soil Sci. Soc. Amer. Proc.* (1939) 4: 94-99.
- LOGERS, W. S. 1935 A soil moisture meter depending on the capillary pull of the soil. *Jour. Agr. Sci.* 25: 326-343.
- SELL, M. B., AND RICHARDS, L. A. 1939 The determination of soil moisture energy relations by centrifugation. *Soil Sci. Soc. Amer. Proc.* (1938) 3: 65-69.
- SELL, M. B. 1940 Soil moisture sorption curves for four Iowa soils. *Soil Sci. Soc. Amer. Proc.* (1939) 4: 51-54.
- (62) RICHARDS, L. A., M. B., DAVIS, F. E., AND BAIR, R. A. 1940 The use of tensiometers for wing soil moisture conditions under corn. *Jour. Amer. Soc. Agron.* 32: 71-72.
- (66) RICHARDS, L. A. 1942 Pore size distribution as a measure of soil structure. *Soil Sci. Soc. Amer. Proc.* (1941) 6: 108-112.

- (67) SCHOFIELD, R. K. 1935 The pF of water in soil. *Trans. Third Internatl. Cong. Soil Sci.* 2: 37-48.
- (68) SCHOFIELD, R. K., AND DA COSTA, J. V. B. 1938 The measurement of the pF in soil by freezing point. *Jour. Agr. Sci.* 28: 644-653.
- (69) SCHOFIELD, C. S. 1945 The measurement of soil water. *Jour. Agr. Res.* 71: 375-402.
- (70) SHAW, C. F. 1929 The measurement of suction forces in soils. *Soil Sci.* 27: 111-115.
- (71) SMITH, R. M., AND BROWNING, D. R. 1948 Soil moisture tension and pore space relations for several soils in the range of the field capacity. *Soil Sci. Soc. Amer. Proc.* (1947) 12: 17-21.
- (72) STOECKELER, J. H., AND AAMODT, E. 1940 Use of tensiometers in regulating watering in forest nurseries. *Plant Physiol.* 15: 589-607.
- (73) VEIHMEYER, F. J. 1929 An improved soil-sampling tube. *Soil Sci.* 27: 147-152.
- (74) VEIHMEYER, F. J., EDLEFSEN, N. E., AND HENDRICKSON, A. H. 1943 Use of tensiometers for measuring the availability of water to plants. *Plant Physiol.* 18: 66-78.
- (75) WADLEIGH, C. H., AND AYERS, A. D. 1945 Growth and biochemical composition of bean plants as conditioned by moisture tension and salt concentration. *Plant Physiol.* 20: 106-132.
- (76) WADLEIGH, C. H. 1946 The integrated soil moisture stress upon a root system in a large container of saline soil. *Soil Sci.* 61: 225-238.
- (77) WADLEIGH, C. H., GAUCH, H. G., AND MAGISTAD, O. C. 1946 Growth and rubber accumulation in guayule as conditioned by soil salinity and irrigation regime. U. S. Dept. Agr. Tech. Bul. 925.
- (78) WALLIHAN, E. F. 1939 Use of tensiometers for soil moisture measurement in ecological research. *Ecology* 20: 403-412.
- (79) WOODRUFF, C. M. 1941 Soil moisture and plant growth in relation to pF. *Soil Sci. Soc. Amer. Proc.* (1940) 5: 36-41.

Foreword

During the 1948 crop season the Colorado, Iowa, New York (Cornell), and North Carolina Agricultural Experiment Stations and the Bureau of Plant Industry, Soils, and Agricultural Engineering, cooperating, undertook a series of field experiments on utilization of phosphorus by crops through the use of radiophosphorus. Preliminary reports of results from these experiments were given at a conference at Beltsville during December, and the interest in this method of experimentation prompted preparation of the papers collected in this issue of *SOIL SCIENCE*. Although the reports on experiments undertaken in the different areas of the United States appear in separate papers, there is sufficient similarity of experiments to allow the reader to compare one with another. Apparently the pattern of phosphorus utilization in one area does not differ greatly from that in another.

The extensive use of radiophosphorus in these field experiments was made possible by the cooperative efforts of a large group of scientists. The preparation and distribution of the fertilizer material containing P^{32} was centered at the Plant Industry Station. W. L. Hill, E. J. Fox, S. B. Hendricks, and L. A. Dean participated in that phase. The assays of the vegetative plant samples, from all field experiments, for P^{31} and P^{32} were conducted in the laboratories of the North Carolina Agricultural Experiment Station under the supervision of N. S. Hall and A. J. MacKenzie. All radiophosphorus used was supplied through the facilities of the Atomic Energy Commission.

F. W. PARKER

UTILIZATION OF PHOSPHORUS BY POTATOES¹

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Investigations have revealed that potatoes give yield response to applications of phosphorus even on soils relatively high in available phosphorus (1, 4). In further studies of phosphorus utilization by potatoes, conducted in Maine with the Katahdin variety in 1947, phosphatic fertilizers labeled with P^{32} were used (5). The results showed that the percentage of phosphorus in the plant from the fertilizer was reduced as the amount of phosphorus in the soil increased. This percentage was increased by increasing the rate of application. Compared with certain other crops, the potato plant derived a higher proportion of its phosphorus from the fertilizer during the latter part of the growing period. This was thought to be related to the limited root system and the relatively short growing season of potatoes.

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This report concerns experiments in Long Island and in North Carolina. The effects of level of soil phosphorus and rate of application on utilization of phosphorus are considered.

MATERIALS AND METHODS

The Long Island experiments were conducted at two locations on Sassafrass silt loam. Locations on a relatively low (149 pounds of P_2O_5) and a medium (868 pounds of P_2O_5) phosphorus level for that area were selected. The North Carolina experiments were conducted in Washington County at two locations on Bladen silt loam. The soils at these locations contained 66 and 240 pounds of P_2O_5 per acre. The phosphorus in the soil was determined by the modified Truog method.

TABLE 1
Dates of field operations

OPERATION	LONG ISLAND		NORTH CAROLINA		STAGE OF GROWTH AT SAMPLING
	149 lb. P_2O_5	868 lb. P_2O_5	66 lb. P_2O_5 *	240 lb. P_2O_5	
Planting.....	April 13	April 16	March 18	March 18	
Sampling 1.....	June 11	June 7	—	April 19	6-8 inches high
2.....	June 21	June 16	April 30	April 30	12-14 inches high
3.....	July 6	July 2	May 12	May 12	Early bloom
4.....	August 2	August 9	June 9	June 9	Before leaves matured

Early growth was greatly delayed in this experiment by wet conditions at planting.

Phosphorus was added at rates of 0, 50, 100, and 200 pounds of P_2O_5 per acre in Long Island and 0, 25, 100, and 200 pounds per acre in North Carolina. Adequate nitrogen and potash were applied. All the fertilizer was placed in bands 3 inches to each side of the seed piece and 2 inches below. The Green Mountain variety was grown in Long Island and the Irish Cobbler variety in North Carolina.

The Long Island plot design consisted of five $27\frac{1}{2}$ -foot rows, with one row for the radioactive measurements, one row for yield measurements, and three rows for guards. In North Carolina, an additional row was included for radioactive measurements, only the 25- and the 100-pound rates received the labeled fertilizer, and the plots were $23\frac{1}{2}$ feet long. Six replications in a randomized t -design were used. For chemical analyses, two replications were combined for each sample, making a total of three samples for each treatment at each harvesting date.

Four sets of samples were taken from the radioactive rows. The first was a thinning sample, for which a single stalk was cut from each hill having more than one shoot. The rows were then divided into thirds. At the next two samplings the tops were harvested. At the last sampling, both tops and tubers were harvested. The dates of field operations are given in table 1.

RESULTS AND DISCUSSION

Percentage of phosphorus in plant derived from fertilizer

The percentage of phosphorus in the plant derived from the fertilizer increased as the rate of application was increased in all four experiments (figs. 1 and 2). This agrees with past results (5). In considering these figures it should be remembered that tubers were included in the fourth sampling.

In Long Island the proportion of phosphorus in the plant derived from the fertilizer was appreciably reduced as the amount of phosphorus in the soil increased (fig. 1). The high phosphorus soil level was very close to the average of

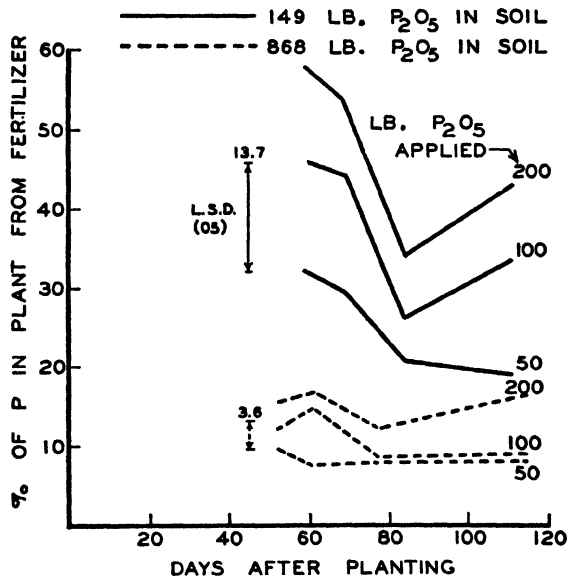


FIG. 1. PERCENTAGE OF PHOSPHORUS IN THE PLANT DERIVED FROM THE FERTILIZER AS AFFECTED BY RATE OF APPLIED PHOSPHORUS AND LEVEL OF AVAILABLE PHOSPHORUS IN THE SOIL

Least significant differences [L. S. D.'s (.05)] are for treatment means.

793 pounds of P_2O_5 per acre found in a survey of the phosphorus status of potato soils in Long Island in 1944 (1). This particular soil had been under intensive cultivation for 40 years and a considerable amount of phosphorus had accumulated. A very low proportion of the phosphorus in the plant was derived from the fertilizer in this soil. The low-phosphorus soil was cleared in 1944, and hence little phosphorus had accumulated. At this location a relatively high proportion of the phosphorus in the plant was derived from the fertilizer.

In North Carolina the spread between the levels of soil phosphorus was not nearly so great, and hence the effect of soil level on phosphorus utilization was not so marked. It is interesting to note (fig. 2) that with the 100-pound rate of

P_2O_5 , except for the first sampling on one soil, more than 60 per cent of the phosphorus in the plant was derived from the fertilizer.

The phosphorus absorption curves of potatoes grown in Long Island, North Carolina, and Maine [1947 data (5)] at relatively low levels of soil phosphorus are compared in figure 3. After the second sampling the percentage of fertilizer phosphorus in the plant derived from the fertilizer dropped off rather sharply in Long Island and Maine. In North Carolina, however, the percentage remained very high. Part of this differences may be related to the somewhat shorter

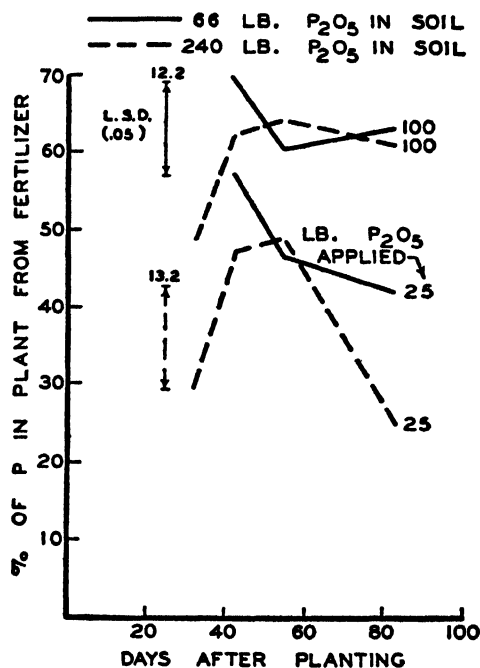


FIG. 2. PERCENTAGE OF PHOSPHORUS IN THE PLANT DERIVED FROM THE FERTILIZER AS AFFECTED BY RATE OF APPLIED PHOSPHORUS AND LEVEL OF AVAILABLE PHOSPHORUS IN THE SOIL

L. S. D.'s (.05) are for treatment means.

growing period in North Carolina. Under this condition the extent of the root system is not so great and the plants utilize a large proportion of the localized application of phosphorus. The period from planting to the final sampling date was 83 days in North Carolina, 90 days in Maine, and 111 (115) days in Long Island. Previous studies have revealed a varietal response to phosphorus (2).²

Pounds of P_2O_5 absorbed from the fertilizer and from the soil

The amount applied exerted the major influence on the pounds of P_2O_5 absorbed from the fertilizer by potatoes (fig. 4). As the rate of applied phosphorus in-

² Hawkins, A. Absorption of major nutrient elements by different varieties of potatoes in Aroostook County, Maine. Doctorate dissertation. [Copy on file in Rutgers University Library, New Brunswick, N. J.]

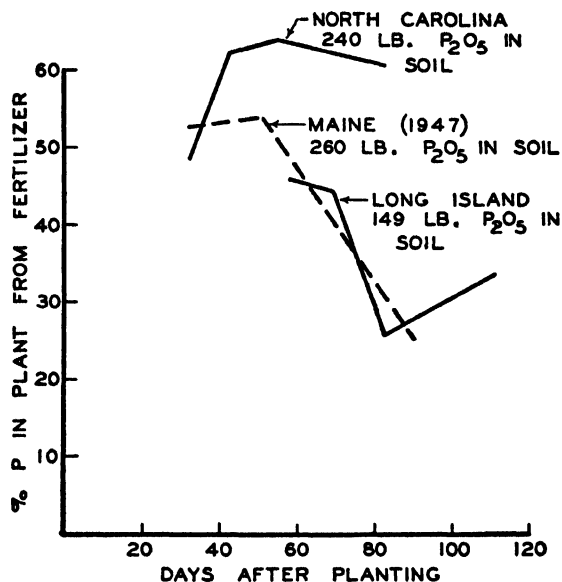


FIG. 3. COMPARISON OF THE PERCENTAGE OF PHOSPHORUS IN THE PLANT DERIVED FROM THE FERTILIZER AT THREE LOCATIONS ON POTATO SOILS RELATIVELY LOW IN AVAILABLE PHOSPHORUS

The rate of applied phosphorus in Long Island and North Carolina was 100 pounds of P_2O_5 per acre; in Maine the rate was 120 pounds.

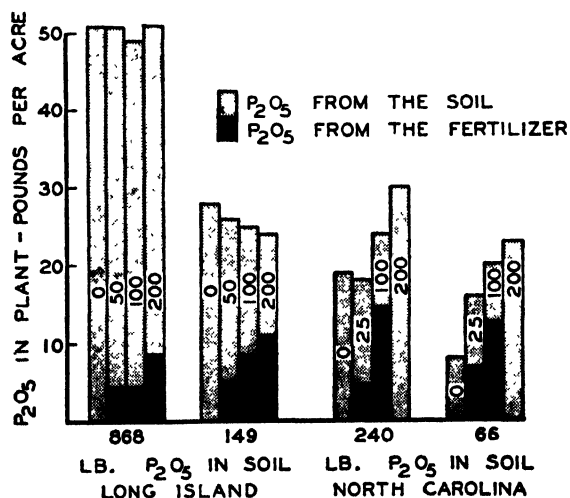


FIG. 4. TOTAL UPTAKE OF P_2O_5 FROM THE FERTILIZER AND FROM THE SOIL AS AFFECTED BY RATE OF APPLIED PHOSPHORUS AND LEVEL OF AVAILABLE PHOSPHORUS IN THE SOIL

Numbers in the bars represent pounds P_2O_5 applied per acre. As P^{32} was not used in the 200-pound rate in North Carolina, the amount of P_2O_5 from the fertilizer could not be determined.

creased, the number of pounds of P_2O_5 absorbed from the fertilizer increased. The percentage of the applied phosphorus absorbed, however, decreased with the higher rates of applied P_2O_5 . In Long Island, at the 100-pound rate on the high-P soil, only 4.2 pounds of the applied phosphorus was utilized, thus leaving 95.8 pounds of the fertilizer phosphorus in the soil (table 2). In North Carolina, on the soil containing 240 pounds P_2O_5 , 14.5 pounds of the fertilizer phosphorus was used. In view of the fact that 150 to 200 pounds of P_2O_5 is applied every year on the potato crop, it is not surprising that the phosphorus level becomes very high in soils cropped continuously to potatoes for any length of time.

The total amount of phosphorus in the potato plant in pounds per acre is influenced greatly by level of soil phosphorus. A high level of soil phosphorus gave a much greater total number of pounds of P_2O_5 in the plants (fig. 4). In North Carolina, applications of fertilizer also increased the total pounds of P_2O_5

TABLE 2

Phosphorus in the plants from the fertilizer and total phosphorus in the plants as related to stage of growth

100 pounds of P_2O_5 per acre applied

LOCATION AND AMOUNT OF P_2O_5 PER ACRE IN SOIL	P_2O_5 IN PLANTS FROM FERTILIZER, LB./A.				TOTAL P_2O_5 IN PLANTS, LB./A.			
	Sampling				Sampling			
	1st	2nd	3rd	4th	1st	2nd	3rd	4th
Long Island 149 lb.	+	4.3	2.7	8.4	+	10	10	25
868 lb.	+	1.5	1.8	4.2	+	10	22	49
North Carolina 66 lb.	—	0.9	3.6	12.6	—	1.2	6.0	20.0
240 lb.. . . .	0.3	4.4	3.7	14.5	0.7	7.1	5.7	24.0

+ Not determined.

in the plants. This was largely due to increases in yields from applied phosphorus (table 4).

Applications of fertilizer phosphorus materially increased the percentage of P_2O_5 in the plants at the first three samplings in North Carolina on both soils (table 3). This effect was not apparent in Long Island. The percentage of phosphorus in the plants was appreciably higher, however, at the higher level of soil phosphorus in the Long Island experiments.

In spite of the relatively high proportion of fertilizer phosphorus in the plant early in the growing season, the number of pounds of P_2O_5 absorbed early from the fertilizer is actually very small (table 2). This is, of course, due to the relatively small amount of growth. This was noted previously (3).

Effect of phosphorus applications on yield

Yields were appreciably increased by applications of phosphorus in North Carolina (table 4). There was a marked growth response to phosphorus on the

low-phosphorus soil throughout the growing season. On the other soil there was an early growth response but it disappeared as the roots extended. There were

TABLE 3
Percentage total P_2O_5 in plants
(Oven-dry basis)

P_2O_5 APPLIED, LB. PER ACRE	SAMPLING				SAMPLING			
	1st	2nd	3rd	4th	1st	2nd	3rd	4th
	Long Island, 149 lb. P_2O_5				Long Island 868 lb. P_2O_5			
0	0.92	0.92	0.53	0.60	1.14	1.10	0.92	0.71
50	1.06	0.96	0.51	0.71	1.12	1.19	0.96	0.71
100	1.08	0.96	0.60	0.60	1.10	1.19	0.96	0.71
200	1.17	1.01	0.64	0.60	1.17	1.28	0.99	0.71
L. S. D. (.05)	0.04	N.S.*	N.S.	N.S.	N.S.	0.04	N.S.	N.S.
C. V. †(%)	4	7	11	12	4	3	10	5
	North Carolina, 66 lb. P_2O_5				North Carolina, 240 lb. P_2O_5			
0	0.56	0.56	0.68	0.50	0.82	0.64	0.54	0.51
25	0.88	0.69	0.50	0.45	1.03	0.86	0.59	0.42
100	1.04	0.88	0.55	0.56	1.16	1.05	0.75	0.50
200	1.28	1.03	0.80	0.64	1.33	1.12	0.93	0.66
L. S. D. (.05)	0.11	0.10	0.16	0.05	0.06	0.04	0.04	0.08
C. V. (%)	6	6	13	10	3	2	3	8

* N.S. = not significant.

† C.V. = coefficient of variation.

TABLE 4

Yields of potatoes as influenced by rate of phosphorus application and level of phosphorus in the soil

P_2O_5 APPLIED	LONG ISLAND		NORTH CAROLINA	
	149 lb. P_2O_5 in soil	868 lb. P_2O_5 in soil	66 lb. P_2O_5 in soil	240 lb. P_2O_5 in soil
lb./A.	cwt./A.	cwt./A.	cwt./A.	cwt./A.
0	212	261	76	200
50*	222	265	134	219
100	213	266	157	233
200	214	272	161	245
L. S. D. (.05)	N.S.	N.S.	18.2	20.9
C. V. (%)	10	9	11	8

* 25 pounds in North Carolina.

no yield responses in Long Island, even at the low level of soil phosphorus. Figures 1, 2, and 3 reveal the fact that the potatoes in North Carolina utilized

fertilizer phosphorus to a greater extent. This may partly explain the yield results obtained.

SUMMARY

Effects of level of soil phosphorus and rate of application on utilization of phosphorus by potatoes were studied in Long Island and North Carolina.

The percentage of phosphorus in the plant derived from fertilizer increased as the rate of application was increased.

The potato plants contained a higher proportion of fertilizer phosphorus when grown on soils low in native phosphorus than when grown on soils high in phosphorus.

As the rate of applied phosphorus was increased, the number of pounds of P_2O_5 absorbed from the fertilizer increased.

In neither Long Island nor North Carolina did level of soil phosphorus greatly affect the pounds of P_2O_5 per acre absorbed from the fertilizer. The total pounds of P_2O_5 absorbed however, was greatly affected by soil level.

The percentage of applied phosphorus utilized was very low. At the 100-pound rate the values ranged from 4.2 to 14.5 per cent in the four experiments.

REFERENCES

- (1) CUMMINGS, R. W., PEECH, M., AND HAWKINS, A. 1946 Nutrient status of soil in commercial potato producing areas of the Atlantic and Gulf Coast: I, II, III. *Soil Sci. Soc. Amer. Proc.* (1945) **10**: 240-256.
- (2) JACOB, W. C., ET AL. The influence of irrigation on the nitrogen, phosphorous and potash requirements of different potato varieties. (In press.)
- (3) HAWKINS, A. 1946 Rate of absorption and translocation of mineral nutrients by potatoes in Aroostook County, Maine, and their relation to fertilizer practices. *J. Amer. Soc. Agron.* **38**: 667-681.
- (4) NELSON, W. L., AND HAWKINS, A. 1947 Response of Irish potatoes to phosphorous and potassium on soils having different levels of these nutrients in Maine and North Carolina. *J. Amer. Soc. Agron.* **39**: 1053-1067.
- (5) NELSON, W. L., ET AL. 1948 Application of radioactive tracer technique to studies of phosphatic fertilizer utilization by crops: II. *Soil Sci. Soc. Amer. Proc.* (1947) **12**: 113-118.

UTILIZATION OF PHOSPHORUS BY TOBACCO¹

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A readily available supply of phosphorus early in the growing season is advantageous in the production of bright-leaf tobacco. The importance of this high level of phosphorus to the nutrition of the tobacco plant has been shown by Moss *et al.* (2) and by Woltz *et al.* (4). Further studies on this problem, using tracer techniques in 1947 (3), showed that placement and rate of phosphorus fertilization affected utilization of this nutrient by the tobacco plant. It was shown that the tracer technique was particularly applicable in field investigations with phosphatic fertilizers.

On the basis of this information, experiments were conducted in 1948 on the effects of placement, rate, and source of applied phosphorus. This paper is concerned with a discussion of the results of these experiments.

MATERIALS AND METHODS

Two soil types were used: Cecil sandy loam and Enon sandy loam. The location of the experiments and pertinent information pertaining to the soils are shown in table 1. The field of Cecil sandy loam had been devoted for several years to general cropping. The two previous crops were wheat and lespedeza.

At the Oxford Tobacco Station use was made of some of the fertility plots in an experiment that was started in 1913 by Moss (2). The column headed "Previous treatment" in table 1 refers to the phosphorus and calcium fertilization during the history of these plots. The minus (−) P plots have not received phosphatic fertilizer during the 35-year period. The plus (+) P plots received a normal application of phosphorus (70 to 100 pounds per acre) every third year on the tobacco crop. The plus (+) Ca plots received a total of 3 tons of dolomitic limestone per acre from 1921 to 1929. The minus (−) Ca plots have not received any limestone during the history of the plots. A 3-year rotation was used in these experiments: tobacco; winter oats—soybeans; winter wheat—weeds. The tobacco was the only crop that was fertilized. The soybeans and weeds were turned under for green manure.

The plots at Rural Hall contained two rows for radioactive measurement, one row for yield measurement, and three guard rows and were 37 feet long. They were laid out in a randomized block design with six replications. One-row plots, 20 feet long were used at the Oxford Station. The treatments and materials as identified by sample number are shown in table 2.

In obtaining samples for chemical analysis, two replications were combined, making a total of three samples for each treatment at each harvest date. Five samplings were made, at 10, 20, 30, 40, and 60 days after transplanting. The first sampling was made just as the plants were recovering from transplanting

¹ North Carolina Journal Series Paper 314. This work was supported in part by a grant from the Industry Phosphate Research Committee.

and before any new growth had taken place; the second, when the plants were showing signs of new growth; the third, about the beginning of the grand period of growth; the fourth, near the middle of the grand period of growth; and the fifth, just as the plants came into full bloom.

The fertilizers were applied with an experimental one-row belt-type distributor.²

TABLE 1
Analyses of Cecil and Enon sandy loams in experimental fields

EXPERIMENT	PREVIOUS TREATMENT*	SOIL	pH	EXCHANGE CAPACITY	EXCHANGE Ca	P ₂ O ₅ †
				me./100 gm.	me./100 gm.	
Rural Hall.....		Cecil	4.8	6.5	1.8	100
Oxford.....	-P-Ca	Enon	5.1	1.5	.3	20
Oxford.....	-P+Ca	Enon	5.5	1.6	.7	20
Oxford.....	+P-Ca	Enon	5.0	1.5	.4	70
Oxford.....	+P+Ca	Enon	5.3	1.7	.8	80

* See text for details.

† Soluble in 0.002 N H₂SO₄

TABLE 2
Fertilizer treatments in experimental plots

TREATMENT NO.	P ₂ O ₅ APPLIED	PLACEMENT	MATERIAL AND SAMPLE NO.*
	lb./A.		
1			
2	40	Mixed in row 4 inches deep 6 inches wide	Superphosphate-2592E
3	80	Mixed in row 4 inches deep 6 inches wide	Superphosphate-2592E
4	40	Mixed in row 4 inches deep 6 inches wide	Ammoniated superphosphate-2593B
5	40	Bands 7 inches apart 4 inches deep	Superphosphate-2592E
6	40	Side-dressed 10 days after planting	Superphosphate-2592E

* Described by Hill *et al.* (1).

It was very dry during the growing period at Rural Hall. Less than 1 inch of rain fell during the course of this experiment. At Oxford the rainfall was ample and well distributed, affording conditions favorable for production of tobacco.

RESULTS AND DISCUSSION

Effect of soil conditions on plant growth and phosphorus utilization

The dry weather conditions at Rural Hall resulted in a relatively small total growth of plants (table 3).

² Developed by G. A. Cumings of the Division of Agricultural Engineering, U. S. Department of Agriculture.

At the Oxford Station there was a large difference in the total growth of plants at the two soil phosphorus levels. The dry weight was approximately 50 per cent greater from the high- than from the low-phosphorus soil. The calcium level did not affect the growth with low soil phosphorus. At the high soil phosphorus level, high calcium resulted in a significant increase in total growth.

The plant contained a higher percentage of phosphorus at the high soil calcium and phosphorus levels than at the low levels.

Figure 1 shows the effect of soil conditions on the uptake of fertilizer phosphorus at the 40-pound rate of application (treatment 2). A larger percentage of the phosphorus in the plant was derived from the fertilizer on the low-phosphorus soil than on the high-phosphorus soil. High soil calcium resulted in a smaller percentage of the phosphorus in the plant from the fertilizer.

TABLE 3
Total growth of tobacco plants at last sampling

P ₂ O ₅ SUPPLIED*	PLACEMENT	PLANT GROWTH†				
		Rural Hall— Cecil Sandy loam	Oxford—Enon sandy loam			
			—P—Ca	—P+Ca	+P—Ca	+P+Ca
lb./A.		lb./A.	lb./A.	lb./A.	lb./A.	lb./A.
0		688	456	507	988	1536
40	Mixed in row	917	1241	1204	1618	1691
80	Mixed in row	943	1612	1733	2085	2190
40	In bands	975	1334		1618	
40	Side-dressed	834	1133		1616	

* From superphosphate.

† Dry matter.

Effect of rate of application of phosphorus

At the Oxford location, an increase in total growth resulted with each increment of applied phosphorus at each of the levels of soil phosphorus and calcium (table 3). At Rural Hall only the first 40-pound increment resulted in an increase in total growth.

Under all of the soil conditions each increment of applied phosphorus resulted in an increase in the percentage content of phosphorus in the plant at the first three samplings. The increase in percentage phosphorus content of the plant in its early stages of development at the high rate of applied phosphorus may account for the increase in total growth, even though the phosphorus content was approximately the same for all plants at the last sampling date.

The increases in percentage of phosphorus in the plant from the fertilizer with increasing rate of applied phosphorus were very similar for each of the soil conditions at the Oxford location. The average effect of increasing rate of applied phosphorus on percentage of phosphorus in the plant from the fertilizer at Oxford is shown in figure 2. There is a striking parallelism between the results

obtained at Oxford and at Rural Hall under a different set of weather conditions.

The effect of increasing rate of applied phosphorus on the uptake of fertilizer phosphorus and soil phosphorus is shown in figure 3. An increase in the rate of applied phosphorus resulted in an increase in the amount of phosphorus taken up from the fertilizer and also from the soil.

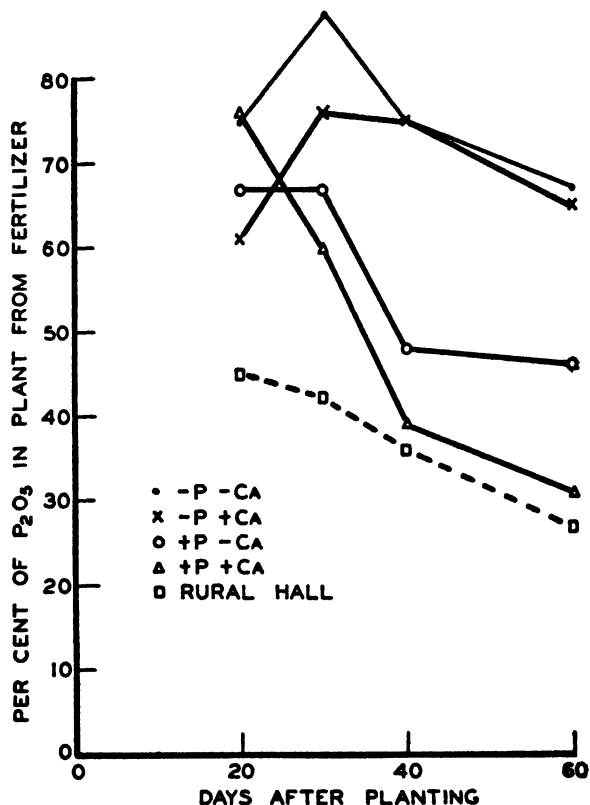


FIG. 1. EFFECT OF SOIL CONDITION ON UPTAKE OF FERTILIZER PHOSPHORUS AT DIFFERENT SAMPLING DATES

Forty pounds of P_2O_5 applied from superphosphate.

Effect of source of phosphorus

There were no significant differences in total growth or percentage content of phosphorus in the plant as a result of applying ordinary or ammoniated superphosphate. Ammoniated superphosphate, however, did show a slight decrease in percentage of phosphorus in the plant from fertilizer. This was true at both locations and was not affected by the soil conditions at the Oxford location.

Effect of placement

At all locations, early growth was stimulated by mixing the phosphorus in the row. At the third sampling, growth on the side-dressed plots was approxi-

mately the same as that on the check plots. As can be seen in table 3, however, these early differences in growth were not manifested in the total dry weight at the last sampling.

In the early part of the season, side-dressing resulted in a lower percentage phosphorus content in the plant than did other placements at Rural Hall and on the low soil phosphorus series at Oxford. At the final sampling, however, no differences in phosphorus content were observed at either of the locations.

In each experiment throughout the growing season, mixing the phosphorus in the row resulted in the highest percentage of phosphorus in the plant from the

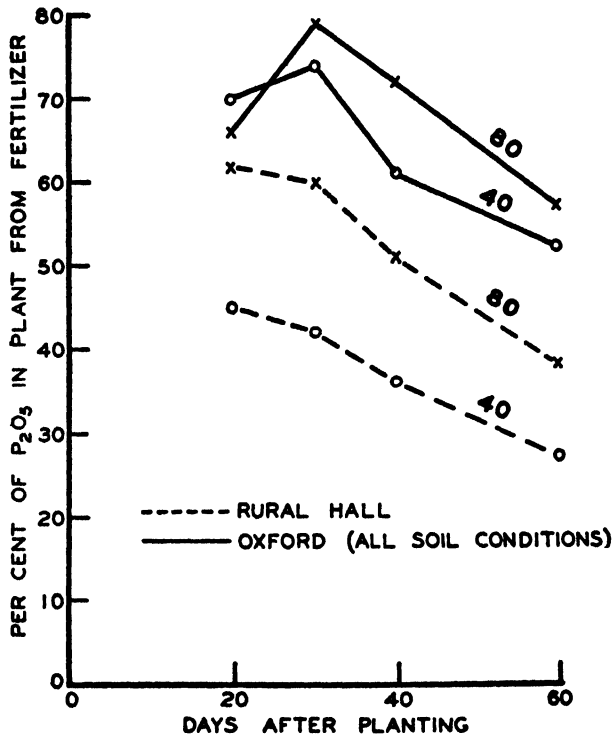


FIG. 2. EFFECT OF RATE OF APPLICATION ON UPTAKE OF FERTILIZER PHOSPHORUS AT DIFFERENT SAMPLING DATES

fertilizer (fig. 4). It is postulated that under these conditions the banding of the phosphate restricted the zone of application in the soil too much for the most efficient use of the phosphorus by the tobacco plant.

At the Rural Hall, where the plant roots were restricted to the lower depth of the soil because of dry weather, a very small percentage of the side-dressed phosphorus was utilized by the plant. At the Oxford location, however, where soil moisture conditions were more conducive to root growth in the top layers of the soil, a larger percentage of the side-dressed phosphorus was utilized. Even under the conditions of ample rainfall, utilization of side-dressed phosphorus in

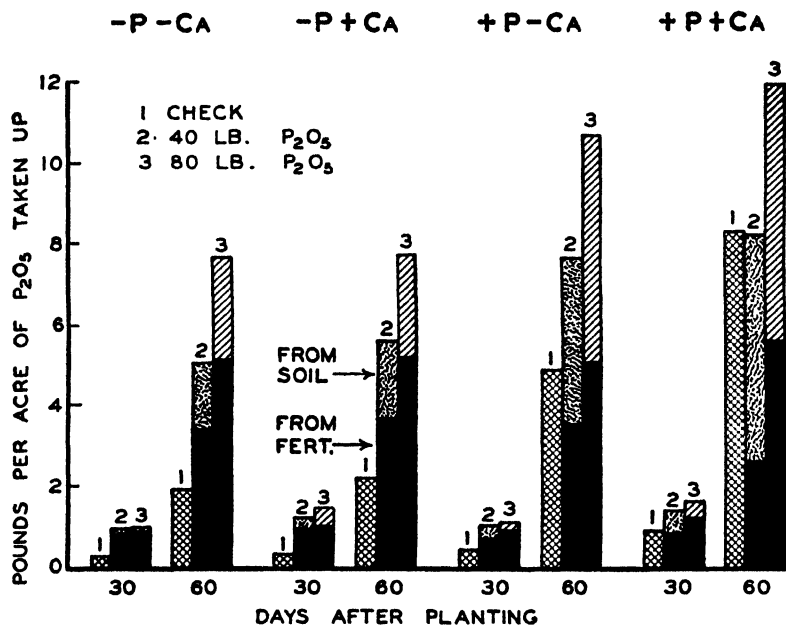


FIG. 3. EFFECT OF RATE OF APPLICATION ON UPTAKE OF PHOSPHORUS AT TWO STAGES OF GROWTH (OXFORD STATION)

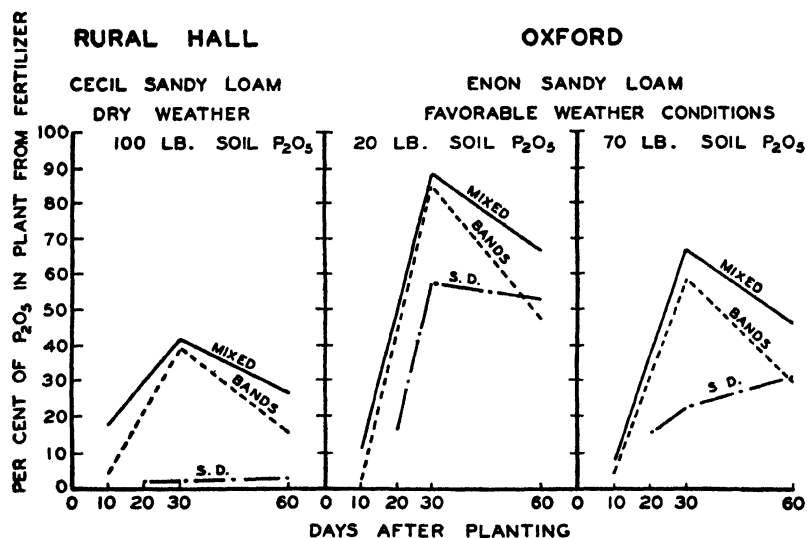


FIG. 4. EFFECT OF PLACEMENT ON UPTAKE OF FERTILIZER PHOSPHORUS

Forty pounds of P_2O_5 applied from superphosphate.

the early stages of growth was considerably below that of the bands and mixed in row. At the final sampling at Oxford, however, the percentage of phosphorus

in the plant from the fertilizer with the side-dressed treatment equalled that with bands. It is further apparent in figure 4 that the level of soil phosphorus greatly influenced the percentage of phosphorus in the plant from the fertilizer.

Figure 5 shows the effect of placement on the uptake of phosphorus from the fertilizer and soil. For all locations at the 30-day sampling period, side-dressing resulted in a low uptake of fertilizer and total phosphorus. At the Rural Hall location, side-dressing resulted in a lower final uptake of fertilizer phosphorus and total phosphorus than did the other two placements. At the Oxford location, the lower uptake of fertilizer phosphorus with band placement and side-dressing was not manifested in the total uptake of phosphorus at the last sampling. It is further evident in figure 5 that the level of soil phosphorus

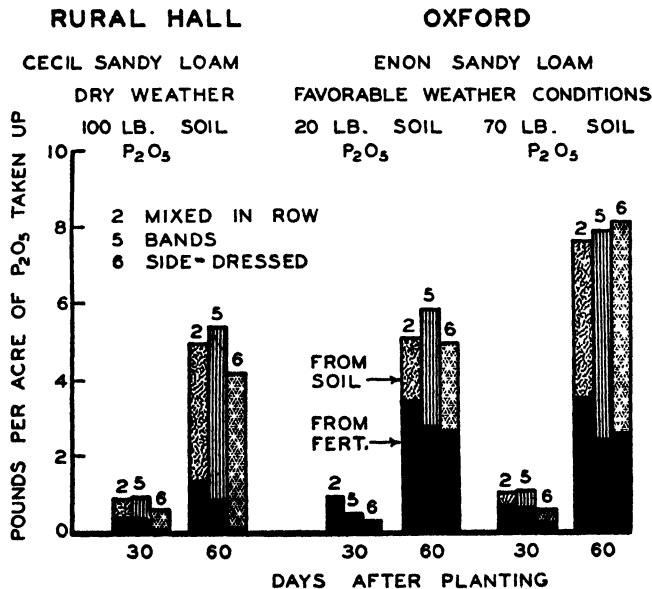


FIG. 5. EFFECT OF PLACEMENT ON UPTAKE OF PHOSPHORUS AT TWO STAGES OF GROWTH

Forty pounds of P_2O_5 applied from superphosphate

under the same soil and weather conditions did not influence the amount of fertilizer phosphorus taken up by the plant. Under these conditions, however, high soil phosphorus did bring about a larger total uptake of phosphorus, which resulted in a lower percentage of phosphorus in the plant from the fertilizer, as is shown in figure 4.

CONCLUSIONS

Increase in soil phosphorus level under comparable climatic and soil conditions resulted in an increase in total growth, an increase in total phosphorus taken up, a decrease in the percentage phosphorus in the plant from the fertilizer, but no differences in the amount of fertilizer phosphorus taken up by the plant.

Increase in calcium level of the soil, or factors associated with such increase, resulted in a lower percentage of phosphorus in the plant from the fertilizer and an increase in total growth at the high level of soil phosphorus.

Increase in rate of applied phosphorus at all locations resulted in an increase in total growth, in amounts of phosphorus in the plant from the fertilizer, and in amounts of phosphorus in the plant from the soil.

No significant differences in total growth were observed between the various placements. Side-dressing did, however, result in a much smaller early growth. Under the dry conditions of the Rural Hall experiment, side-dressing resulted in a very low utilization of phosphorus. Under the more favorable soil moisture conditions at Oxford, side-dressing resulted in a lower utilization of fertilizer phosphorus than did banding or mixing in the row, at all but the last sampling date.

REFERENCES

- (1) HILL, W. L., FOX, E. J., AND MULLINS, J. F. 1949 Preparation of radioactive phosphate fertilizers for plant-utilization tests by tracer methods. *Indus. and Engin. Chem.* **41**: 1328-1334.
- (2) MOSS, E. G., ET AL. 1927 Fertilizer tests with flue-cured tobacco. U. S. Dept. Agr. Tech. Bul. 12.
- (3) NELSON, W. L., ET AL. 1948 Application of radioactive tracer technique to studies of phosphatic fertilizer utilization by crops: II. *Soil Sci. Soc. Amer. Proc.* (1947) **12**: 113-118.
- (4) WOLTZ, W. G., REID, W. A., AND COLWELL, W. E. Sugar and nicotine in cured bright tobacco as related to mineral element composition *Soil Sci. Soc. Amer. Proc.* (1948) 13. (In press.)

UTILIZATION OF PHOSPHORUS AS AFFECTED BY PLACEMENT: I. CORN IN IOWA¹

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Proper placement of hill and row fertilizers for corn at planting time is of primary importance to corn-belt farmers. Consequently, a number of field studies have been conducted in the past in attempts to arrive at satisfactory solutions to this problem. In many cases, however, comparisons of different methods of placement have yielded inconclusive results. Experiments in Iowa, for example, have shown that it is difficult to draw definite conclusions, from yield data, as to the superiority of one method of placement over another, inasmuch as the differences in yield are often small and the experimental error is large. If one method of placement were superior to others by as little as 1 or 2 bushels per acre, however, this would be of great economic importance.

The purpose of the studies reported in this paper was to determine the relative efficiency of phosphorus utilization by corn with different placements of superphosphate, as revealed by studies with P^{32} as a tracer supplemented by determination of dry matter and grain yields. Although the principal emphasis was laid on comparisons of depth of placement, the number of fertilizer bands and the rate of application also were investigated.

MATERIALS AND METHODS

Studies on methods of placement of superphosphate were conducted at three locations in the Clarion-Webster soil area. The soils selected were Clarion loam and Webster silty clay loam. The locations are designated herein as Clarion, Webster I, and Webster II. The available phosphorus level of the soils by the Bray² extractant, employing 0.025 *N* HCl in 0.03 *N* NH_4F was 14.5, 3.5, and 6 pounds per acre, respectively. The corresponding pH values were 5.5, 7.1, and 6.7.

The different treatments or placements included in each experiment and the rates of superphosphate applied, expressed as pounds P_2O_5 per acre, were as follows:

Number	Placement	Rate
1	None	0
2	$\frac{1}{2}$ inch deep—1 band	30
3	2 inches (approx. seed depth)—1 band	30
4	5 inches deep—1 band	30
5	2 inches deep—2 bands	30
6	2 inches deep—1 band	60

¹ Joint contribution. Iowa Journal Paper J-857. Report of a study made under the Research and Marketing Act of 1946. This work was supported in part by a grant from the Industry Phosphate Research Committee.

² Bray, R. H. Determination of total, organic, and available forms of phosphorus in soils. *Soil Sci.* 59: 39-45. 1945.

All plots at each location received 30 pounds of N and 40 pounds of K_2O per acre applied in a continuous band along the row. The treatments were randomized within each block and replicated six times.

The six-row plots included one radioactive row, one row for obtaining yields of dry matter at various stages of growth, two rows for estimation of yield at maturity, and two border rows. Distance between rows was 42 inches, and the row length was 30 feet.

Corn (Iowa Hybrid 939A) was drilled, by a two-row corn planter, with a spacing of approximately 7 inches between kernels. The fertilizer then was applied with a belt delivery machine in a continuous band along the row. The corn was planted and the phosphate applied from May 21 to 28. Drought at the Clarion location necessitated replanting on June 11. The first or thinning samples were taken June 8 and 9 at the Clarion and Webster I locations when the plants were 4 to 6 inches high, and on June 25 at the Webster II location when the plants were 7 to 10 inches high. The stand was thinned to 12,800 plants per acre at the Clarion location, and to 14,940 plants at the Webster I and II locations. The second sampling was made about 8 days later than the first, when the plants were 8 to 12 inches high at the Clarion and Webster I locations and 18 to 22 inches high at the Webster II location. The third sampling was made 13 to 22 days after the second, when the plants were 30 to 40 inches high. The last sampling was made from August 24 to September 3, when the ears were in the roasting stage.

The samplings were made according to the following scheme: The first was taken in conjunction with the thinning of the P^{32} and P^{31} rows to the desired uniform stand. The second consisted of removing all plants from one third of the P^{32} row and an equal number from an adjacent P^{31} dry-matter row. Only three treatments—No's. 1, 3, and 4—were sampled at this time. At the third and fourth sampling, leaves only were taken from the P^{32} rows whereas dry-matter samples of all of the above-ground portion of the plant were taken from the adjacent P^{31} dry-matter row. For treatments 1, 3, and 4 the third samples consisted of leaves from one third of the P^{32} row and dry-matter samples from one third of the adjacent P^{31} row. For treatments 2, 5, and 6, not sampled at the second date, leaf and dry matter samples were similarly taken except that half of each row was used. For the fourth and final sampling, the P^{32} leaf and the P^{31} dry-matter samples were taken from the area remaining in the P^{32} and P^{31} rows.

RESULTS

Yields of dry matter at different stages of growth and final grain yields

Yields of dry matter at different stages of growth in relation to method of fertilizer placement are given in table 1. Various comparisons between placements are shown in the footnotes of the table.

The data indicate that growth response to phosphorus (none *vs.* seed level) was significant throughout the period sampled on the two Webster locations. Earlier evidence of response at the Clarion location had disappeared by the time plants had reached the roasting-ear stage. The latter observation may be related to the relatively high content of available phosphorus in the Clarion soil.

Seed-level placement was significantly better than shallow placement at the Webster II location on the first and third sampling dates. There still is evidence of this difference at the final sampling. The deep *vs.* seed-level comparison indicates that the latter placement was superior on at least one sampling date at each location.

It is apparent that the yields of dry matter have served to differentiate between placements and have indicated the instances where responses to phosphate occurred. More adequate sampling for estimating dry-matter yields probably would have revealed the differences more clearly. This improvement is worthy of consideration in future studies of this kind.

Yields of grain were not significantly different with the various placements, although a response to phosphorus occurred at the two Webster locations. The

TABLE 1

Effect of different placements of superphosphate on yields of corn plants at different stages of growth and on grain yields†

PLACE- MENT†	CLARION					WEBSTER I					WEBSTER II				
	Dry matter‡				Grain	Dry matter				Grain	Dry matter				Grain
	1	2	3	4		1	2	3	4		1	2	3	4	
1	3.2	10.1 (a**)	296 (a**)	4896	40.4	4.8	14.0 (a**)	522	4906 (a*)	46.2	11.3 (a*)	76.5	377 (a**)	6759 (a*)	77.5
2	3.2	—	372 (c**)	4820	39.1	4.3	—	540	5318	58.6	10.2 (b**)	—	367 (b*)	7003	80.7
3	3.1	12.7	414	4800	44.0	4.4	18.7	632	4728	60.4	13.4	83.5	477	7508	80.5
4	3.0	10.8	287 (d**)	4749	44.7	3.4	13.6 (d**)	500	5673	56.2	10.3 (d**)	71.4	419	7920	83.4
5	3.3	—	369	5156	39.2	4.2	—	574	5395	58.9	11.5	—	435	7751	85.2
6	3.2	—	360	4841	44.0	4.9	—	484	5376	52.3	13.4	—	459	7315	87.9

† Yields of dry matter are expressed as pounds of oven-dry plant material per acre. See text for stage of growth at each sampling date. Grain yields are in bushels per acre.

‡ See text for placement methods and rates.

§ Samplings show:

- (a) Significant difference between none and seed level (2-inch) placement.
- (b) Significant difference between shallow ($\frac{1}{2}$ -inch) and seed level (2-inch) placements
- (c) Significant difference between shallow ($\frac{1}{2}$ -inch) and deep (5-inch) placements
- (d) Significant difference between deep (5-inch) and seed-level (2-inch) placements

* Significant at 5 per cent level

** Significant at 1 per cent level.

low yields obtained from the Clarion plots can be attributed to late germination as a result of drought. Unfavorable moisture conditions for germination and growth early in the season, nitrogen deficiency which developed before tasseling, and late planting date probably account for the low yields from the Webster I plots. In the Webster II plots, moisture conditions were favorable for early germination, but from July 1 to August 31 moisture definitely was a factor limiting ear development.

Utilization of fertilizer phosphorus by corn plants

Percentage of phosphorus in plant derived from fertilizer. Where yields of dry matter were shown to be significantly related to method of placement, it is to be expected that the use of P³² tracer would reveal these relationships even more strikingly. This is borne out by the data in table 2.

TABLE 2
Percentage of phosphorus in corn plants derived from fertilizer in relation to method of placement, rate of application, and stage of growth

PLACEMENT†	CLAYTON SAMPLINGS‡				WEBSTER I SAMPLINGS				WEBSTER II SAMPLINGS			
	1	2	3	4	1	2	3	4	1	2	3	4
2	9.1	—	9.4(a)**	5.9	0.2	—	16.5(a)*	(b)**	12.7	—	21.8(a)**	(b)**
3	8.2	50.4	16.8	6.3	10.3	12.5	20.5	15.0	27.5	26.7	25.5	9.2
4	0.5 (c)*	12.7(c)**	13.3	4.4(c)**	3.3	8.9	24.5	15.6	1.4	9.1(c)**	13.5 (c)*	8.6(c)*
5	17.4	—	11.4	5.4	17.1	—	27.0	15.8	25.1	—	30.5	11.8
6	9.8	—	13.8	7.6	12.0	—	28.5	16.0	57.9(d)*	—	32.6	10.8

† See text for placement methods and rates. Bands approximately 2 inches from seed, except with deepest placement (no. 4), where the interval was approximately 3 inches.

‡ See text for stage of growth at each sampling date. Samplings show:

(a) Significant difference between shallow ($\frac{1}{4}$ inch) and seed-level (2 inch) placements.

(b) Significant difference between shallow ($\frac{1}{4}$ inch) and deep (5 inch) placements.

(c) Significant difference between deep (5 inch) and seed-level (2 inch) placements.

(d) Significant difference between 30 and 60 pounds P_2O_5 .

* Significant at 5 per cent level.

** Significant at 1 per cent level.

TABLE 3

Percentage recovery of applied phosphorus in relation to method of placement, rate of application, and stage of growth

PLACEMENT*	PERCENTAGE RECOVERY OF APPLIED P AT SAMPLING DATES†			
	1	2‡	3	4
<i>Clarion</i>				
1	—	—	—	—
2	0.007	—	0.78	3.66
3	0.006	0.113	1.64	4.12
4	0.001	0.019	1.00	3.05
5	0.013	—	1.03	3.82
6	0.004	—	0.62	2.52
<i>Webster I</i>				
1	—	—	—	—
2	0.002	—	1.91	5.88
3	0.008	0.075	2.77	7.94
4	0.003	0.030	2.94	7.40
5	0.013	—	3.24	7.10
6	0.009	—	1.60	3.97
<i>Webster II</i>				
1	—	—	—	—
2	0.038	—	2.13	6.64
3	0.116	0.682	3.06	6.33
4	0.004	0.198	1.42	6.26
5	0.095	—	3.66	9.08
6	0.152	—	1.96	3.93

* See text for placement methods and rates. Bands were approximately 2 inches from seed, except with deepest placement (no. 4), where interval between seed and fertilizer band was approximately 3 inches.

† See text for stage of growth at each sampling date.

‡ Only three treatments were sampled on the second sampling date.

The following comparisons between placements and rates of application are of chief interest:

Shallow ($\frac{1}{2}$ inch *vs.* seed-level (2 inch) placement.

Shallow ($\frac{1}{2}$ inch) *vs.* deep (5 inch) placement.

Deep *vs.* seed-level placement.

One band *vs.* two bands (both at seed level).

30 pounds P_2O_5 *vs.* 60 pounds P_2O_5 per acre.

The footnotes accompanying table 2 point out the instances where such comparisons reveal significant differences. At none of the three locations did there appear to be significant differences in percentage phosphorus derived from the fertilizer when 1-band and 2-band placements were compared. At only one location (Webster II) did the 60-pound rate or P_2O_5 furnish more phosphorus to

the plants than did the 30-pound rate; this was evident only at the initial sampling date.

Seed-level placement proved to be superior to shallow placement on the third sampling date at the three locations. This also was evident at the Webster I location when corn was in the roasting-ear stage. There is evidence that less fertilizer phosphorus was absorbed from the shallow placement prior to the first sampling at the two Webster locations. It is well to point out that in every case variation of P^{32} analyses between replicates was great for the first samples taken. Fortunately, sampling error decreased considerably as the plants became older.

Significant differences occurred between the shallow and deep placements on the third and fourth samplings at the two Webster locations. Phosphorus utilization was greater however, with the deep placement at the Webster I location and greater with the shallow placement at the Webster II location. There appears to be no real difference between deep and shallow placement in the absorption of fertilizer phosphorus from the Clarion soil.

The contrast between absorption of fertilizer phosphorus from seed-level and deep placements was particularly marked at the Webster II location and at the Clarion site, the seed-level placement being more favorable from the standpoint of phosphorus delivery to the plant.

Percentage recovery of phosphorus applied in superphosphate. The percentage recovery of applied phosphorus is presented in table 3. Percentage recovery of phosphorus applied as superphosphate was particularly low on the Clarion soil. Whether this was due to the relatively high available phosphorus content of the soil (14.5 pounds per acre), to the late planting, or to both factors is not clear. It appears that recovery was somewhat higher on the Webster I location than on the Webster II location, but the difference, if any, is slight.

The percentage recovery was consistently less from the higher than from the lower rate of application. In general, it appears that the very young plants had recovered more phosphorus from the fertilizer placed at seed level than from the shallow or deep placements. The contrast between deep and seed-level placements is particularly evident in the second sampling period, and generally is observed in the third period.

SUMMARY

Field experiments with corn conducted at three locations in north-central Iowa, using superphosphate containing P^{32} , show that the percentage of the phosphorus derived from the fertilizer is influenced by the position of the fertilizer in respect to the seed. Placement of the fertilizer at seed depth and in bands on one or both sides of the seed generally resulted in a greater utilization of the applied phosphorus by the plant than placement in a single band above the level of the seed or in a single band 3 inches below the seed.

Increases in yield of total dry matter of the above-ground portions of the plant, particularly during the early stages of growth, also show the seed-level placement is superior to either of the other two methods. Final grain yields showed no consistent differences between the methods of placement.

The percentage of the total phosphorus in the plants derived from the fertilizer varied considerably at different stages of growth. In general, the values increased up to the third sampling (the plants averaged 30 to 45 inches in height), when the values ranged from about 10 to 30 per cent. At the fourth date of sampling, when the plants were in the roasting-ear stage, the values ranged mostly between 5 and 15 per cent.

Recovery of the phosphorus applied in the fertilizer by the plants in the roasting-ear stage varied from a maximum of about 4 per cent on the Clarion soil to maxima of 8 to 9 per cent on the Webster soils.

UTILIZATION OF PHOSPHORUS AS AFFECTED BY PLACEMENT:

II. COTTON AND CORN IN NORTH CAROLINA¹

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Placement affects the efficiency of fertilizer utilization. Direct measurement of this utilization is possible through the use of labeled materials.

In an experiment on cotton in 1947, placement of phosphorus directly with the seed as compared with placement in bands 3 inches to each side of and 2 inches below the seed increased the percentage of phosphorus derived from the fertilizer in the young plant². The total P_2O_5 in the plant was also considerably increased at this early stage of growth by placing the phosphorus with the seed. Placement had no effect on phosphorus utilization later in the growth period, however, and no effect on final yields of seed cotton.

The objective of the investigations reported in this paper was to study further the effects of placement of superphosphate on the utilization of phosphorus by cotton and corn throughout the growing period.

MATERIALS AND METHODS

Cotton

Experiments were conducted at two locations on Norfolk sandy loam. The soils at these locations contained 67 and 288 pounds of P_2O_5 (soluble in 0.002 *N* sulfuric acid) per acre, respectively. The soil low in phosphorus had been out of cultivation for about 50 years. The high-phosphorus soil had been farmed to cotton and tobacco for many years and, hence, showed a considerable build-up of phosphorus.

The following acre-treatments were used:

1. 15 pounds of P_2O_5 spread directly on the seed by hand.
2. 15 pounds of P_2O_5 spread directly on the seed and 35 pounds in bands 10 inches to each side and 4 inches below the seed.
3. 50 pounds of P_2O_5 in bands 3 inches to each side and 2 inches below the seed.
4. 50 pounds of P_2O_5 mixed in the row about 4 inches deep and 6 inches wide.
5. 50 pounds of P_2O_5 broadcast and disced in.

Treatment 3 was made with a two-row Iron Age fertilizer distributor and planter equipped with belts for use in experimental fertility work. Treatments 2, 4, and 5 were made with a one-row belt-type distributor³. Adequate nitrogen and potash were applied in bands 3 inches to each side and 2 inches below the seed.

¹ Joint contribution: North Carolina Journal Series Paper 310. This work was supported in part by a grant from the Industry Phosphate Research Committee.

² Nelson, W. L., et al. Application of radioactive tracer technique to studies of phosphatic fertilizer utilization by crops: II. *Soil Sci. Soc. Amer. Proc.* (1947) 12: 113-118. 1948.

³ Developed by G. A. Cumings, U. S. Department of Agriculture.

The plots contained two rows for radioactive measurements, one row for yield measurement, and three guard rows and were 23.5 feet long. They were laid out in a randomized block design with six replications. In obtaining the samples for chemical analyses, two replications were combined, making a total of three samples for each treatment at each harvesting date.

Three sets of plant samples, composed of the aboveground portion, were taken from the rows receiving radioactive phosphorus. The first sample was taken by thinning the plants, leaving a final stand of three plants per foot. The rows were then divided in half for the second and third samplings. On the low-phosphorus soil two thinning samples were made in treatments 1 and 3. The dates of the field operations are given in table 1.

Corn

The corn experiment was on the low-phosphorus Norfolk sandy loam adjacent to the cotton experiment. The soil contained 49 pounds of P_2O_5 (soluble in 0.002 *N* sulfuric acid) per acre. The fertilizer placement treatments and methods

TABLE 1
Dates of field operations for cotton

OPERATION	67 LB. P_2O_5 IN SOIL*	288 LB. P_2O_5 IN SOIL	STAGE OF GROWTH
Planting	April 17	April 16	
Sampling 1	May 28	May 22	One pair of true leaves
2	July 1	June 22	First squares appearing
3	August 9	August 9	About half of bolls full size

* In treatments 1 and 3 a sampling was made May 14, when the plants were in the cotyledon stage.

used were the same as those used on cotton except that in treatment 2 the 35-pound portion was mixed in the row about 4 inches deep and 6 inches wide. Six-row plots, 34 feet long, were used. The plot arrangement, number of replications, design, and method of sampling and compositing for chemical analyses were similar to those used in the cotton experiment.

Six sets of plant samples were taken from the radioactive rows: the first three by thinning the entire plot, and the last three from respective thirds of the two rows. Corn hybrid, Dixie 17, was planted on April 23. The six sampling dates were May 14, May 24, June 1, June 14, June 28, and August 16. The corresponding plant heights and stages of growth were 2-3 inches, 5-7 inches, 10-12 inches, 18-20 inches, 34-36 inches, and late roasting-ear stage.

RESULTS AND DISCUSSION

Percentage of phosphorus in plant derived from fertilizer

Cotton. On the low-phosphorus soil, samples in treatments 1 and 3 were taken 27 days after planting. The plants were still in the cotyledon stage. At this time, treatment 1 showed that a much higher percentage of the phosphorus in

the plant was derived from the fertilizer than in treatment 3 (fig. 1). Apparently at this stage of growth very few of the cotton roots had reached the band 3 inches to the side of the seed. This effect of phosphorus placed with the seed has been observed before. In 2 weeks, however, the absorption of fertilizer phosphorus in treatment 3 was considerably above that in treatment 1.

Mixing the phosphorus in the row gave a relatively high proportion of the phosphorus in the plant from the fertilizer. Broadcasting and discing in gave distinctly less utilization. The low availability resulting from thoroughly mixing the phosphorus with the soil is in agreement with results of other investigations.

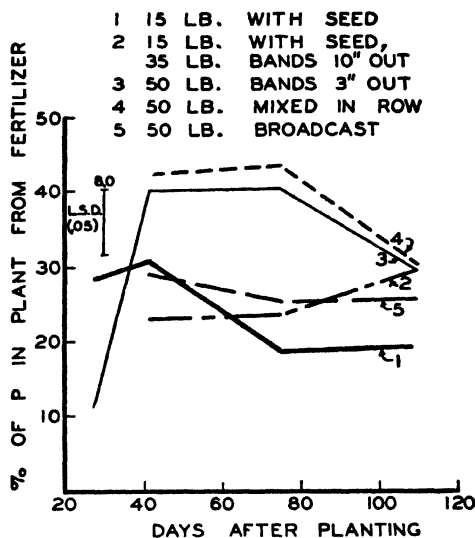


FIG. 1. PERCENTAGE OF PHOSPHORUS IN THE COTTON PLANT DERIVED FROM THE FERTILIZER AS AFFECTED BY PLACEMENT

Low-phosphorus soil (67 pounds P_2O_5). L. S. D. (.05) is for treatment means.

The shape of the utilization curve for treatment 2 shows an increase in the percentage of phosphorus derived from the fertilizer at the last sampling. At this time a considerable proportion of the roots apparently were in the area of the localized bands of phosphorus 10 inches from the row.

Somewhat the same effects of placement were observed in the high-phosphorus soil (fig. 2), but the differences were generally of lesser magnitude. The results from treatment 2 on both low- and high-phosphorus soils point toward the need for further study of multiple-band placement at varying distances from the seed.

Corn. Comparison of the 50-pound rates of application shows that at the first sampling the proportion of phosphorus in the plant derived from the fertilizer was lowest with the band placement, next lowest with the "mixed in row," and

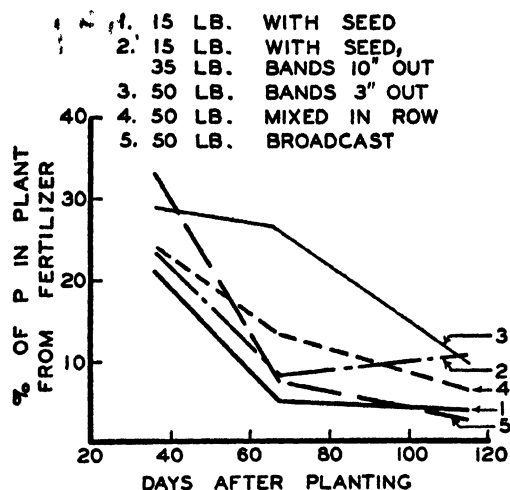


FIG. 2. PERCENTAGE OF PHOSPHORUS IN THE COTTON PLANT DERIVED FROM THE FERTILIZER AS AFFECTED BY PLACEMENT

High-phosphorus soil (288 pounds P_2O_5). L. S. D. (.05) at second sampling was 4.7 per cent. The differences among treatments were not significant at the first and third samplings.

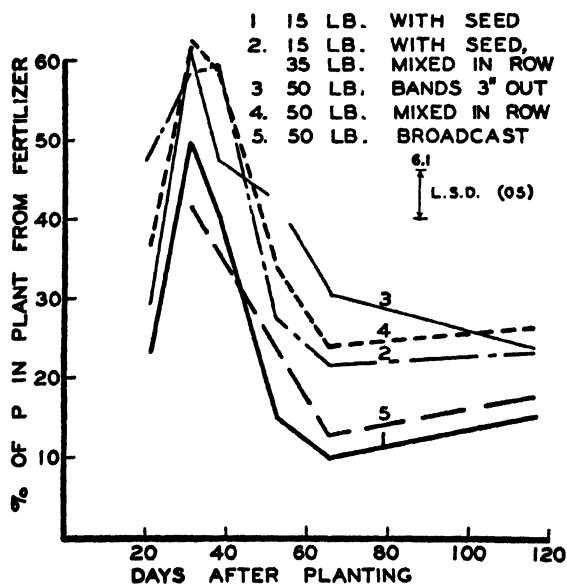


FIG. 3. PERCENTAGE OF PHOSPHORUS IN THE CORN PLANT DERIVED FROM THE FERTILIZER AS AFFECTED BY PLACEMENT

L. S. D. (.05) is for treatment means.

highest with a combination of the "with seed" and "mixed in the row" (fig. 3). This indicates that early utilization of fertilizer phosphorus was greater when

small amounts were placed close to the seed than when it was all placed in bands. This difference was not apparent at the later samplings, as the band placement was as good as any of the placements. The broadcast placement was the least efficient method of application, and throughout the season the proportion of

TABLE 2

P₂O₅ in plant from the fertilizer and total P₂O₅ in cotton and corn plants as related to stage of growth

PLACEMENT*	P ₂ O ₅ IN PLANTS FROM FERTILIZER, LB./A.			TOTAL P ₂ O ₅ IN PLANTS, LB./A.		
	Cotton—67 lb. P ₂ O ₅ in soil					
	Sampling, days after planting			Sampling, days after planting		
	41	75	114	41	75	114
1	0.03	0.47	1.30	.10	2.9	7.7
2	0.03	0.67	2.72	.13	2.9	9.9
3	0.04	1.03	1.81	.10	2.5	6.8
4	0.04	1.04	2.55	.09	2.3	7.9
5	0.03	0.61	2.15	.10	2.5	7.2
	Cotton—288 lb. P ₂ O ₅ in soil					
	Days after planting			Days after planting		
	36	67	115	36	67	115
	1	0.04	0.29	0.48	.19	5.8	10.8
2	0.05	0.56	1.37	.22	6.9	17.4
3	0.07	1.43	1.64	.24	5.3	16.4
4	0.08	0.88	1.46	.34	6.8	17.7
5	0.09	0.42	0.96	.27	5.5	16.9
	Corn—49 lb. P ₂ O ₅ per acre					
	Days after planting			Days after planting		
	31	66	117	31	66	117
	1	0.10	0.64	3.5	0.21	6.7
2	0.15	1.27	5.0	0.27	6.2	21.1
3	0.13	2.51	5.2	0.23	8.5	21.8
4	0.17	1.92	5.0	0.29	8.4	18.8
5	0.09	0.93	3.8	0.20	7.2	21.2

* See text for placement methods and rates.

phosphorus in the plant derived from the fertilizer was about the same as that derived from the 15-pound application with the seed.

Amount of P₂O₅ absorbed from fertilizer and soil

Cotton. Both placement and level of soil phosphorus influenced the pounds of P₂O₅ absorbed from the fertilizer by cotton (table 2). In both soils at the last sampling, treatment 2 gave the greatest increase over the previous sampling in

terms of pounds of fertilizer P_2O_5 absorbed. Broadcasting the fertilizer resulted in a relatively low uptake. This is particularly noticeable on the soil of high-phosphorus fertility.

At the 50-pound rate with treatment 2, 5.4 per cent of the applied P_2O_5 was absorbed by the cotton on the low-phosphorus soil and only 2.7 per cent on the high-phosphorus soil. It is interesting to note that on the low-phosphorus soil with the 15-pound rate with seed 8.7 per cent of the applied phosphorus was absorbed.

Placement had little consistent effect on the total pounds of P_2O_5 in the plants (table 2). On the high-phosphorus soil, however, the total pounds of P_2O_5 in the plants was practically double that in the plants grown on the low-phosphorus soil. This is in agreement with past results. Placement had little effect on the percentage of P_2O_5 in the plants except at the cotyledon stage of growth. At this time placement with the seed increased the percentage of P_2O_5 in the plants.

Corn. The uptake of fertilizer phosphorus by the plant at the roasting-ear stage was higher in placements 2, 3, and 4 than that in the broadcast treatment (table 2). There was no appreciable difference, however, in total P_2O_5 content of the plant.

The recovery from 50-pound applications of phosphorus was very low (about 7 to 10 per cent) even on this low-phosphorus soil. With the 15-pound rate of application, the recovery was relatively high (23 per cent), but unfortunately no other placements were made at that rate for comparison.

Effect of phosphorus application on growth and final yields

There was an early vegetative growth response to phosphorus application on both corn and cotton. The magnitude of the response varied with placement, the broadcast placement producing the least. These growth responses correlate with results obtained on the utilization of fertilizer phosphorus in the early stages of growth.

In cotton production this rapid early development is essential. Damage to the developing squares and young bolls from insect attacks later in the growing season exerts a tremendous influence on cotton yields. Hence, any practice or group of practices that will hasten development of the fruit past this vulnerable stage should be very valuable. Cotton yields were increased by phosphate application on the low-phosphorus soil (table 3). Fifteen pounds of P_2O_5 with the seed gave a lower yield than the other treatments, probably because of deficiency of phosphorus. Placement had no effect on yields at the 50-pound rate on either soil.

Although corn showed a significant vegetative growth response to phosphorus application at the first five samplings, drought conditions which started just prior to the fifth sampling retarded subsequent growth and limited yields to about 65 to 70 bushels per acre. There was no significant difference in the yield or phosphorus content of corn grain due to phosphorus application or placement.

Even though there was no final yield difference between these treatments,

relative differences in efficiency of these placements are revealed by the use of the tracer technique.

The data indicate that it is possible to effect early growth stimulation by one placement and to increase further the uptake of fertilizer phosphorus at late stages of growth by another placement. In view of these placement data and the characteristic phosphorus utilization by various crops,⁴ it appears that multiple placement of phosphorus could be "tailored" to the crop.

Further placement work is planned with a newly developed machine⁵ that will give accurate and uniform fertilizer distribution and will make possible a large number of placement combinations.

TABLE 3

Yields of cotton and corn as influenced by placement of fertilizer phosphorus and level of soil phosphorus

PLACEMENT*	SEED COTTON, POUNDS PER ACRE		CORN, BUSHELS PER ACRE
	67 lb. P_2O_5 in soil	288 lb. P_2O_5 in soil	49 lb. P_2O_5 in soil
None	834	2112	66.1
1	1088	2348	66.2
2	1502	2225	67.6
3	1403	2287	66.1
4	1304	2163	74.4
5	1298	2410	72.3
L. S. D. (.05)	454	N.S.†	N.S.
C. V. (%)	29	16	8

* See text for placement methods and rates.

† N. S. = not significant.

SUMMARY

The effect of placement on the utilization of phosphorus was studied at two levels of soil phosphorus on cotton and at one soil level on corn.

In the cotton plant, placement of the phosphorus with the seed gave a higher percentage of phosphorus derived from the fertilizer in the cotyledon stage. When phosphorus was placed in bands 10 inches out, there was an increase in the uptake of fertilizer phosphorus at the last sampling.

In corn, placement of phosphorus with the seed and mixed in the row gave the highest percentage of phosphorus in the plant derived from the fertilizer at the first sampling. This difference was not found later in the season.

Placement influenced the pounds of P_2O_5 absorbed from the fertilizer in both cotton and corn. Broadcasting gave a relatively low total uptake.

⁴ Krantz, B. A., Nelson, W. L., Welch, C. D., and Hall, N. S. A comparison of phosphorus utilization by crops. This issue of *Soil Science*.

⁵ This machine is being developed jointly by the North Carolina Agricultural Experiment Station and the U. S. Department of Agriculture.

On the low-phosphorus soil, cotton absorbed approximately twice as much fertilizer phosphorus as on the high-phosphorus soil. In one treatment on the low-phosphorus soil 5.4 percent of the applied P_2O_5 was absorbed, whereas only 2.7 per cent was absorbed on the high-phosphorus soil.

The total pounds of P_2O_5 absorbed and the percentage of P_2O_5 in the plant were affected to a greater extent by level of soil phosphorus than by placement.

Although there was no yield difference between placements, the differences in the efficiency of phosphorus utilization were shown by the tracer technique.

UTILIZATION OF PHOSPHORUS FROM VARIOUS FERTILIZER MATERIALS: I. ORCHARD GRASS AND LADINO CLOVER IN NEW YORK¹

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This experiment was designed to measure the yield and the chemical and botanical composition of a ladino-clover-orchard-grass association as influenced by methods and rates of applying four radioactive phosphate fertilizers. The proportion of total phosphorus uptake which was derived from the radioactive fertilizers was also measured.

MATERIALS AND METHODS

A field experiment was established in May 1948 on Mardin silt loam which had not been fertilized for many years. The pH of the soil was 5.3 and the readily soluble P_2O_5 content was 81 pounds per acre, as determined by the modified Truog method.²

A good seedbed was prepared by plowing and harrowing the soil. The fertilizer treatments were randomized in three complete blocks on plots 3 by 20 feet with a 2-foot border. Four sources of phosphates were surface-broadcast at rates of 50 and 100 pounds of P_2O_5 and drilled at the rate of 100 pounds of P_2O_5 per acre. Lime and K_2O at the rate of 1,000 and 50 pounds per acre, respectively, were used with all the phosphate treatments. The lime- K_2O treatment, without phosphorus, served as the check treatment. After the fertilizers were applied, a mixture of 5 pounds of inoculated ladino clover seed and 12 pounds of orchard grass per acre was surface-broadcast.

Herbage samples were hand-plucked for chemical analyses on July 8, when the ladino clover and orchard grass were approximately 3 and 5 inches high, respectively. The herbage was sampled for yields, chemical analyses, and botanical composition on July 26 and September 9. The species were in a vegetative growth stage, 6 and 12 inches in height. The botanical separates, orchard grass and ladino clover, were used for chemical analyses and acre-yield computations.

RESULTS AND DISCUSSION

The total dry-matter yields of mixed herbage or their botanical constituents (orchard grass and ladino clover) did not differ for the four phosphate fertilizers for either of the two harvests.³ The addition of phosphates to the lime- K_2O treatment did not increase the yields. The herbage yields for the lime- K_2O treatment were higher than those for untreated plots.

¹ This work was supported in part by a grant from the Industry Phosphate Research Committee.

² Peech, M., et al. Methods of soil analysis for soil fertility investigations. *U. S. Dept. Agr.*, Circular No. 757: 1-25, 1947.

³ All differences as discussed in this paper are based on statistical significance.

The ladino clover yields for the first harvest were increased when 100 pounds P_2O_5 was drilled as compared with a broadcast application (table 1). The mean yields for all phosphates were 222 and 238 pounds for the broadcast applications of 50 and 100 pounds of P_2O_5 , respectively, as compared with 340 pounds of ladino clover for a drilled application at the rate of 100 pounds of P_2O_5 per acre. This trend occurred with all four phosphate fertilizers. The yields of mixed herbage, ladino clover, or orchard grass were not increased when the broadcast application of P_2O_5 was increased from 50 to 100 pounds per acre.

The percentage P_2O_5 content of ladino clover and orchard grass was not influenced by the four sources of phosphates or by the rates and methods of application. The percentage P_2O_5 content of ladino clover ranged from 0.53 to 0.58 for all harvests and all treatments. The mean P_2O_5 content of orchard grass was 0.67, 0.66 and 1.05 per cent for the first, second, and third harvests, respectively. Orchard grass was higher in total P_2O_5 content than ladino clover for all harvests, all sources of phosphates, and all rates and methods of application. The percentage of P_2O_5 in ladino clover did not differ for the seasonal harvests. Conversely,

TABLE 1

Dry-matter yields per acre of mixed herbage, ladino clover, and orchard grass as influenced by rate and method of phosphate application

SOURCE OF PHOSPHATE FERTILIZER	RATE PER ACRE AND METHOD OF APPLICATION	MIXED HERBAGE*			LADINO CLOVER			ORCHARD GRASS		
		July 26	Sept. 9	Total	July 26	Sept. 9	Total	July 26	Sept. 9	Total
Mean for all phosphates	50 lb. broadcast	1338	950	2288	222	554	776	930	368	1298
	100 lb. broadcast	1330	1018	2348	238	614	852	876	381	1257
	100 lb. drilled	1492	1005	2497	340	593	933	980	392	1372

* Yields of ladino clover and orchard grass are based on hand separations of the mixed herbage. The weed fraction is included in the data for mixed herbage.

with orchard grass the P_2O_5 content of the herbage harvested on September 9 was much higher than for the two earlier dates. It is possible that the percentage of leaves of orchard grass was higher for the harvest made on September 9 than for the two previous harvests. Such large differences in P_2O_5 content do not appear to be associated with differential growth stage, however, as the herbage for all harvests was in a vegetative condition of growth.

The percentages of P_2O_5 in orchard grass and ladino clover that were absorbed from four sources of phosphates under different methods and rates of application are presented graphically in figures 1 to 4.

Ladino clover treated with superphosphate absorbed 22.5, 25.7 and 20.8 per cent of its P_2O_5 from the fertilizer in the first, second, and third seasonal harvests, respectively (fig. 1). These values (means for methods and rates of application) were higher than those for any other sources of phosphates. Ladino clover also absorbed more phosphorus from calcium metaphosphate than from either dicalcium or tricalcium phosphate for the first harvest. The percentages of P_2O_5 absorbed by ladino clover in the first harvest from the four sources of phosphates

were as follows: superphosphate, 22.5; calcium metaphosphate, 13.7; tricalcium phosphate, 6.6; and dicalcium phosphate, 6.5. As the season advanced, there was an increase in P_2O_5 absorption from the fertilizer from tricalcium and dicalcium phosphates, but P_2O_5 intake from these sources was lower than for superphosphate.

The mean percentage of P_2O_5 absorbed by ladino clover for three harvests from four phosphate fertilizers under different methods and rates of application are given in figure 2. When broadcast applications of superphosphate were increased from 50 to 100 pounds of P_2O_5 per acre, the percentage of P_2O_5 in ladino clover absorbed from the fertilizer increased from 14.8 to 24.2. When superphosphate at the rate of 100 pounds of P_2O_5 was drilled, 30.1 per cent of the P_2O_5 in

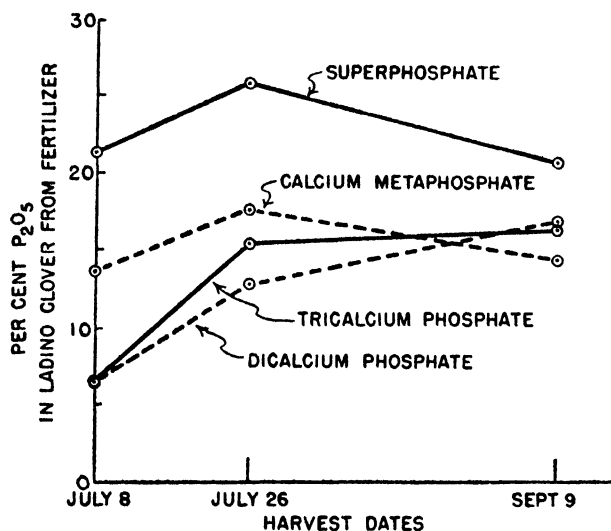


FIG. 1. PERCENTAGE OF P_2O_5 ABSORBED FROM FOUR PHOSPHATE FERTILIZERS BY LADINO CLOVER AT THREE DATES

Mean values for methods and rates of application.

ladino clover was absorbed from the fertilizer. These are significant increases for rates and methods of application.

The amount of P_2O_5 absorbed from calcium metaphosphate was lower than that from superphosphate. The trends with respect to method and rates of application for these two sources of phosphates, however, were similar.

Ladino clover treated with dicalcium and tricalcium phosphates broadcast at the rate of 50 pounds of P_2O_5 per acre absorbed 6.8 and 7.9 per cent of the P_2O_5 from the fertilizers, respectively. These percentages were less than that for superphosphate at the same rate of application. As the rate of broadcast applications was increased from 50 to 100 pounds of P_2O_5 per acre there was an increase in the amount of phosphorus absorbed from both the dicalcium and the tricalcium phosphates. Drilling of these two phosphates did not result in an increase in the amount of P_2O_5 absorbed from the fertilizer. The amount of phos-

phorus in ladino clover absorbed from dicalcium and tricalcium phosphates, applied at the rate of 100 pounds of P_2O_5 per acre, was about the same as for

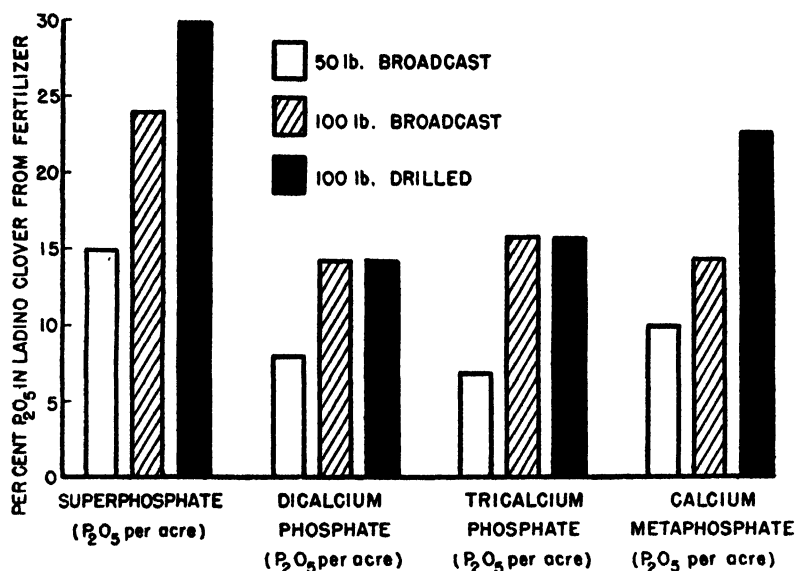


FIG. 2. INFLUENCE OF SOURCES AND OF RATES AND METHODS OF APPLYING VARIOUS PHOSPHATE FERTILIZERS ON THE PERCENTAGE OF PHOSPHORUS ABSORBED BY LADINO CLOVER

Mean for three herbage harvests.

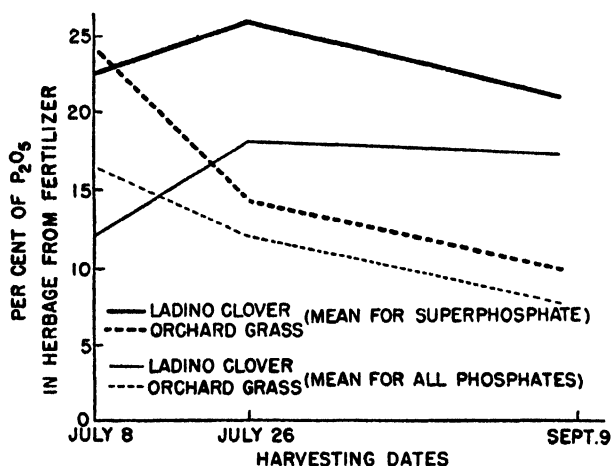


FIG. 3. DIFFERENTIAL PHOSPHORUS ABSORPTION FROM FERTILIZER BY LADINO CLOVER AND ORCHARD GRASS GROWN IN ASSOCIATION

superphosphate that was applied at the rate of 50 pounds of P_2O_5 per acre (fig. 2).

Orchard grass and ladino clover differed in phosphorus absorption (fig. 3).

Ladino clover absorbed more than 20 per cent of its phosphorus from superphosphate for the three harvests. Conversely, orchard grass absorbed 24 per cent of its phosphorus from superphosphate at the first harvest, but then decreased as the season advanced, until only 10 per cent was obtained in the September harvest. The data for mean values of all phosphates displayed similar trends but of different percentages for the two species (fig. 3).

These differential responses in phosphorus uptake by ladino clover and orchard grass may have practical implications. After seedling establishment, a much smaller percentage of P_2O_5 from the fertilizer was absorbed by orchard grass than by ladino clover. These results indicate (a) that orchard grass absorbed the less available soil phosphates more efficiently than did ladino clover and (b) that phosphorus fertilization is of importance for seedling establishment of orchard grass and ladino clover and for maintenance of ladino clover.

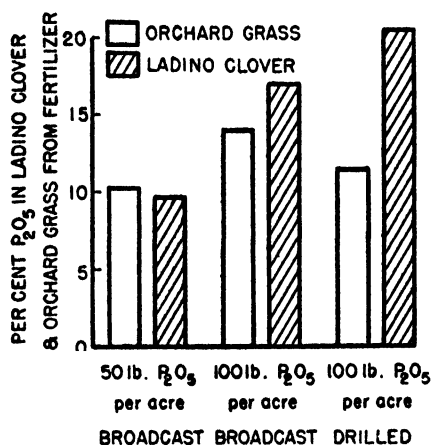


FIG. 4. INFLUENCE OF METHOD AND RATE OF PHOSPHATE FERTILIZATION ON AMOUNT OF PHOSPHORUS ABSORBED FROM FERTILIZERS BY LADINO CLOVER AND ORCHARD GRASS

Mean values for all sources of phosphates and for three herbage sampling dates.

Orchard grass and ladino clover differed in the amount of P_2O_5 absorbed from the fertilizers when methods and rates of application are considered (fig. 4). Ladino clover showed increases in P_2O_5 absorption from the fertilizers as the broadcast applications were increased from 50 to 100 pounds of P_2O_5 per acre. The responses with orchard grass showed a similar trend for these two rates of broadcast applications, but of a lesser magnitude. With ladino clover, more P_2O_5 was absorbed from the drilled fertilizers than for the broadcast applications, whereas with orchard grass the reverse occurred. It will be recalled that ladino clover yields were somewhat higher with drilled than with surface-applied fertilizers. Hence, drilling may be an efficient method of applying fertilizers for ladino clover. This legume is stoloniferous, and nutrients absorbed from band applications would be conducted laterally to parts of plants not rooted in fertilized zones. It may also be possible to obtain desired yields with lower rates of fertilizer for drill than for broadcast applications.

SUMMARY

A mixture of orchard grass and ladino clover was seeded on plots treated with four sources of radioactive phosphate fertilizers. Two methods and two rates of application were used. Data on yield, botanical and chemical composition, and phosphorus absorbed from fertilizers were obtained.

The yields and P_2O_5 content of ladino clover and orchard grass were not associated with source of phosphate and rate of application. The average yield of ladino clover for the first harvest was higher for the drilled than for the broadcast application of phosphates.

The amount of P_2O_5 uptake by ladino clover from the fertilizer was higher for superphosphate at all sampling periods than for the other phosphate fertilizers. During early season more fertilizer phosphorus was absorbed from calcium metaphosphate than from dicalcium or tricalcium phosphates. There was an increase in the amount of phosphorus absorbed from the four phosphate fertilizers as the broadcast applications were increased from 50 to 100 pounds of P_2O_5 per acre. With superphosphate and calcium metaphosphate more fertilizer phosphorus was absorbed from the drilled than from the broadcast applications.

Orchard grass and ladino clover differed in percentage of P_2O_5 absorbed from the fertilizers. Ladino clover absorbed more than 20 per cent of its phosphorus from the fertilizer during all three sampling periods. The absorption for orchard grass was much lower except for the first sampling period. A larger percentage of phosphorus from the fertilizer was absorbed by ladino clover from drilled applications than from broadcast applications. The reverse occurred with orchard grass.

The practical implications of these preliminary data are discussed.

UTILIZATION OF PHOSPHORUS FROM VARIOUS FERTILIZER¹ MATERIALS: II. COTTON AND CORN IN NORTH CAROLINA¹

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The usual criteria for evaluating phosphatic materials has been by comparisons of crop yields. By use of the tracer technique, additional information on the efficiency of various sources is readily obtainable. This paper compares the relative efficiency of superphosphate, ammoniated superphosphate, alpha tricalcium phosphate, dicalcium phosphate, and calcium metaphosphate glass.

MATERIALS AND METHODS

Cotton

Experiments on cotton were conducted on Norfolk sandy loam at two locations varying in phosphorus fertility, one containing 67 and the other 288 pounds of P_2O_5 per acre. The sources indicated in table 1 were applied at rates of 50 and 100 pounds of P_2O_5 per acre. These materials as identified by sample number (table 1) are described by Hill *et al.*² The phosphorus, nitrogen, and potash mixture was applied in bands 3 inches to each side and 2 inches below the seed.

The plots contained two rows for radioactive measurements, three guard rows, and one yield row and were 23.5 feet long. They were laid out in a randomized block design with three replications. The cotton was sampled at the following three stages of growth: first, one pair of true leaves; second, first squares appearing; and third, about half of the bolls full size.

Corn

Superphosphate, calcium metaphosphate, and alpha tricalcium phosphate, applied at the rate of 50 pounds of P_2O_5 per acre, were compared in an experiment conducted on Norfolk sandy loam that contained 319 pounds P_2O_5 (soluble in 0.002 *N* sulfuric acid) per acre. The fertilizer was placed as described for cotton. The plots contained two rows for radioactive measurements and two guard rows, 30 feet long. They were laid out in a randomized block design with six replications. Corn hybrid U. S. 282 was planted on June 4.

All replicates were harvested and analyzed separately at each of three sampling dates. The first sample was a thinning sample, and the second and third samples were taken from respective halves of the two radioactive rows. The corn was sampled on June 21, July 30, and August 27. The stages of growth at the three

¹ Joint contribution: North Carolina Journal Series Paper 311. This work was supported in part by a grant from the Industry Phosphate Research Committee.

² Hill, W. L., Fox, E. J., and Mullins, J. F. Preparation of radioactive phosphate fertilizers for plant-utilization tests by tracer methods. *Indus. and Engin. Chem.* **41**: 1328-1334. 1949.

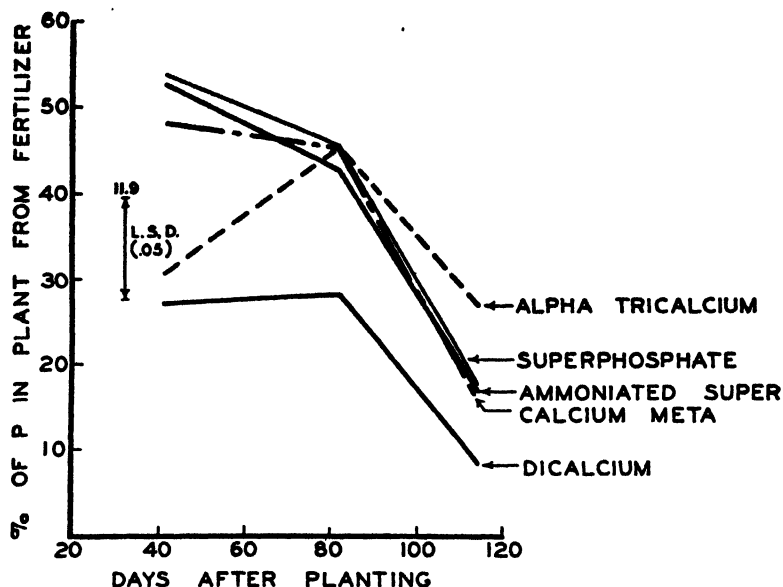


FIG. 1. PERCENTAGE OF PHOSPHORUS IN THE PLANT DERIVED FROM THE FERTILIZER AS INFLUENCED BY THE SOURCE OF PHOSPHORUS FOR COTTON ON NORFOLK SANDY LOAM CONTAINING 67 POUNDS P_2O_5 PER ACRE

The rate of application was 50 pounds P_2O_5 per acre. The L. S. D. (.05) is for treatment means.

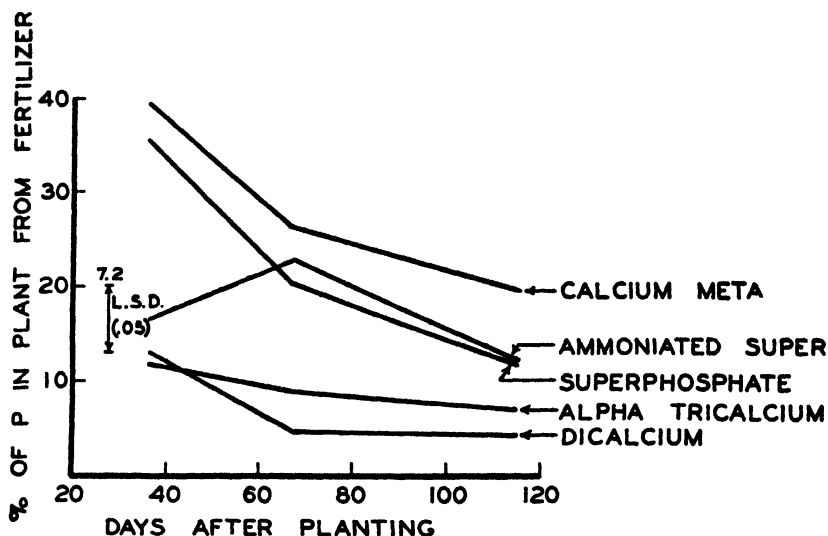


FIG. 2. PERCENTAGE OF PHOSPHORUS IN THE PLANT DERIVED FROM THE FERTILIZER AS INFLUENCED BY THE SOURCE OF PHOSPHORUS FOR COTTON ON NORFOLK SANDY LOAM CONTAINING 288 POUNDS P_2O_5 PER ACRE

The rate of application was 50 pounds P_2O_5 per acre. The L. S. D. (.05) is for treatment means.

Sampling dates were 8–10 inches in height, 45–50 inches in height, and late roasting-ear stage, respectively.

RESULTS AND DISCUSSION

Percentage of phosphorus in the plant derived from the fertilizer

Cotton. On the low-phosphorus soil the percentage of phosphorus in the plant derived from dicalcium phosphate was distinctly lower than that from the other

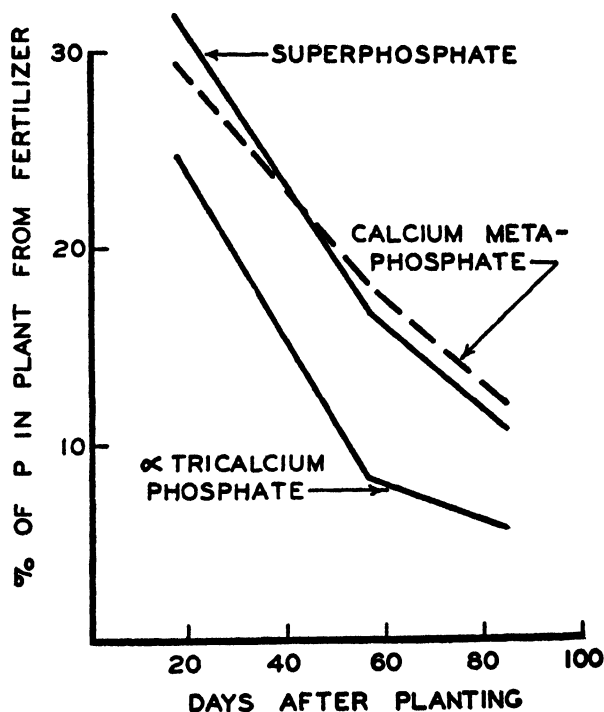


FIG. 3. PERCENTAGE OF PHOSPHORUS IN THE PLANT DERIVED FROM THE FERTILIZER AS INFLUENCED BY THE SOURCE OF PHOSPHORUS FOR CORN ON NORFOLK SANDY LOAM CONTAINING 319 POUNDS P_2O_5 PER ACRE

The rate of application was 50 pounds P_2O_5 per acre. The L. S. D.'s (.05) for the three samplings were 6.8, 4.0, and 3.1 per cent, respectively. The coefficients of variation for the three samplings were 23, 27, and 27 per cent, respectively.

fertilizers. The results for the 50-pound rate of P_2O_5 are shown in figure 1. There were no differences among the other four sources. The results obtained with the 100-pound rate showed a very similar relationship among the sources.

On the high-phosphorus soil, dicalcium phosphate again gave the lowest proportion of fertilizer phosphorus in the plant (fig. 2). On this soil, however, alpha tricalcium was not so effective as the other three sources. At the second and third sampling, the percentage of fertilizer phosphorus in the plant was somewhat greater from calcium metaphosphate than from superphosphate or ammoniated

TABLE 1

P₂O₅ in plants from the fertilizer and total P₂O₅ in plants as related to stage of growth
50 pounds P₂O₅ applied per acre

SOURCE OF P ₂ O ₅ *	P ₂ O ₅ IN PLANTS FROM FERTILIZER, LB./A.			TOTAL P ₂ O ₅ IN PLANTS, LB./A.		
	Cotton—67 lb. P ₂ O ₅ in soil					
	Sampling, days after planting			Sampling, days after planting		
	41	75	114	41	75	114
None	—	—	—	0.07	2.7	13.0
Ammoniated superphosphate.....	0.09	1.1	2.0	0.17	2.5	10.7
Superphosphate.....	0.06	1.3	3.6	0.13	2.8	15.4
Alpha tricalcium phosphate	0.03	1.1	2.7	0.10	2.5	10.8
Dicalcium phosphate	0.03	0.8	1.0	0.11	3.0	12.8
Calcium metaphosphate	0.07	1.6	2.4	0.17	3.5	11.7
L.S.D. (.05)	N.S.	0.6	0.8			
C. V. (%).....		36	37			
	Cotton—288 lb. P ₂ O ₅ in soil					
	Days after planting			Days after planting		
	36	67	115	36	67	115
None.....	—	—	—	0.11	5.2	17.6
Ammoniated superphosphate.....	0.02	0.9	3.0	0.12	3.7	21.1
Superphosphate	0.07	1.2	1.9	0.19	6.1	17.6
Alpha tricalcium phosphate	0.01	0.6	1.6	0.08	6.2	25.3
Dicalcium phosphate	0.01	0.2	1.5	0.15	4.7	20.5
Calcium metaphosphate...	0.07	1.4	4.1	0.24	5.2	23.7
L.S.D. (.05)	N.S.	N.S.	N.S.			
C. V. (%).....	56	25	50			
	Corn—319 lb. P ₂ O ₅ in soil					
	Days after planting			Days after planting		
	17	56	84	17	56	84
None	—	—	—	0.03	18.1	31.9
Superphosphate	0.13	3.4	3.5	0.41	21.0	33.1
Alpha tricalcium phosphate.....	0.09	1.5	1.8	0.37	18.4	31.7
Calcium metaphosphate	0.12	3.5	3.9	0.40	19.2	33.7
L.S.D. (.05)	0.03	0.8	0.9			
C. V. (%).....	27	27	27			

* Sample numbers: ammoniated superphosphate, 2593a; superphosphate, 2592b; alpha tricalcium phosphate, 2959a; dicalcium phosphate, 2959a; calcium metaphosphate, 2596a.

superphosphate. The results obtained with the 100-pound rate showed similar relationships among the various sources.

These data seem to indicate that there is an interaction between the level of ✓

soil phosphorus and the efficiency of different phosphate sources, particularly of alpha tricalcium phosphate and calcium metaphosphate.

Corn. Corn plants receiving phosphorus as superphosphate and as calcium metaphosphate were consistently higher in percentage of phosphate derived from the fertilizer than those receiving alpha tricalcium phosphate (fig. 3). There was no appreciable difference in the utilization of phosphorus from superphosphate and calcium metaphosphate. The percentage of phosphorus in the plant derived from each of the three fertilizer materials decreased consistently throughout the season. The general shapes of these curves were similar to those reported previously.

TABLE 2

*Percentage total P_2O_5 in plants as affected by source of phosphorus
50 pounds P_2O_5 applied per acre*

SOURCE OF P_2O_5	COTTON						CORN		
	67 lb. P_2O_5 in soil			288 lb. P_2O_5 in soil			319 lb. P_2O_5 in soil		
	Sampling, days after planting			Sampling, days after planting			Sampling, days after planting		
	41	82	114	36	67	115	17	56	84
None .....	.50	.63	.54	.70	.80	.66	1.03	.57	.50
Ammoniated superphosphate .....	.65	.56	.54	.72	.77	.84	—	—	—
Superphosphate .....	.69	.55	.56	.85	.76	.79	1.35	.60	.50
Alpha tricalcium phosphate .....	.58	.60	.52	.46	.79	.83	1.17	.60	.50
Dicalcium phosphate .....	.60	.54	.53	.47	.77	.85	—	—	—
Calcium metaphosphate .....	.66	.58	.48	.69	.76	.83	1.37	.60	.48
L.S.D. (0.5)	N.S.	N.S.	N.S.	N.S.	N.S.	N.S.	0.12	N.S.	N.S.
C. V. (%)	19	9	16	21	4	11	9	9	10

Amount of P_2O_5 absorbed from the fertilizer and from the soil

Cotton. The pounds of P_2O_5 absorbed from the fertilizer varied with the source of phosphorus applied. The absorption of P_2O_5 from dicalcium phosphate was lower than from any of the other sources on both low- and high-phosphorus soils at the second and third samplings (table 1). On the high-phosphorus soil the absorption from alpha tricalcium phosphate was also relatively low. The absorption from calcium metaphosphate, however, was very high.

There was no consistent effect of source of phosphate on the total pounds of P_2O_5 in the plants at either location (table 1). Soil level had a marked effect, however: the plants on the high-phosphorus soil contained approximately 60 per cent more total P_2O_5 , expressed on the basis of pounds per acre. Sources had virtually no effect on the percentage of P_2O_5 in the plants (table 2).

Corn. The pounds of P_2O_5 absorbed from alpha tricalcium phosphate were lower than those from the other two sources of phosphate at all three samplings of corn

(table 1). There was little difference in uptake of P_2O_5 from calcium metaphosphate and from superphosphate.

The total phosphorus uptake by the plants was not influenced appreciably by phosphate application or source at any sampling time (table 1). At the first sampling the percentage of P_2O_5 in the plant was appreciably lower with alpha tricalcium as the source than with the superphosphates (table 2).

Yields

Cotton. Yields of seed cotton, produced at either location, showed no significant differences for the different sources of phosphorus. There was a response to the first increment of phosphorus on both soils. On the low-phosphorus soil, the yields for 0 P_2O_5 , the average for the 50-pound rates of all sources, and the average for the 100-pound rates of all sources was 1,459, 1,929, and 2,048 pounds of seed cotton per acre, respectively; on the high-phosphorus soil the corresponding yields were 2,049, 2,335, and 2,432 pounds per acre.

Corn. There was no growth response to phosphorus at any sampling. This was one of very few cases in which no early growth differences were apparent between the phosphated and the unphosphated plants. The reason for this situation is probably a combination of the high level of native soil phosphorus and the excellent growing conditions immediately after planting. The corn grain yield was about 70 bushels per acre.

SUMMARY

The effect of sources of phosphorus on its utilization by cotton and corn was studied. Superphosphate, alpha tricalcium phosphate, and calcium metaphosphate were compared on both cotton and corn. Ammoniated superphosphate and dicalcium phosphate were also included in the cotton experiments.

In cotton, on both a low- and a high-phosphorus soil, the lowest percentage of phosphorus was derived from dicalcium phosphate. Compared with the percentage derived from superphosphate on a high-phosphorus soil, that from alpha tricalcium phosphate was lower, that from calcium metaphosphate was higher. Similar results were obtained at the 50- and 100-pound rates on both soils.

In corn, the percentage of phosphorus derived from alpha tricalcium phosphate was lower than that from superphosphate and calcium metaphosphate. This relationship was consistent throughout the growing season.

UTILIZATION OF PHOSPHORUS FROM VARIOUS FERTILIZER MATERIALS: III. OATS AND ALFALFA IN IOWA ¹

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The availability, to crops, of phosphorus in different phosphate fertilizers is of considerable economic importance in the Midwest. Although numerous field experiments have been conducted in the past, it is often difficult to assess properly the availability of the phosphorus in the carrier through yield data alone. It is believed that the labeling of the phosphorus in various carriers with P^{32} will permit a much more rapid and sounder evaluation. The Iowa data presented in this report represent the first of several seasons' contemplated investigations with labeled phosphorus carriers.

MATERIALS AND METHODS

Identical experiments were performed on each of the following soils: Webster silty clay loam of pH 6.0 and containing 7 pounds of available phosphorus ²; Webster silty clay loam of pH 6.7 and containing 5 pounds of available phosphorus; and Clarion loam of pH 5.6 and containing 14 pounds of available phosphorus.

Treatments were dicalcium phosphate, alpha tricalcium phosphate, superphosphate, and calcium metaphosphate, each at the rate of 40 pounds of P_2O_5 per acre, and no phosphate. These materials as identified by sample number (table 1) are described by Hill *et al.*³ Six replications were employed at each location using a randomized block arrangement. The size of each plot was 24 feet by 56 inches (eight 7-inch drill rows). The nonradioactive fertilizer was broadcast uniformly over an area 9 feet by 56 inches on each end of the plot. The corresponding P^{32} fertilizer was applied on the center area, which was 6 feet by 56 inches. All plots received broadcast applications of 60 pounds of ammonium nitrate and 100 pounds of muriate of potash per acre. After broadcasting, the plots were disked and the oats sown with a drill. The alfalfa was seeded broadcast except on Webster soil of pH 6.7, where it was drilled.

Samples of the oats were taken from each of the P^{32} subplots and from one of the adjacent P^{31} subplots at each sampling date. The remainder of the plot was harvested at maturity to determine the grain yield. The estimate of dry matter for each sampling was obtained by adding the dry weights of samples from the P^{31} and P^{32} portions of each plot. The six replicates of each treatment were com-

¹ Report of a study made under the Research and Marketing Act of 1946. Joint contribution: Journal Paper J-1252. This work was supported in part by a grant from the Industry Phosphate Research Committee.

² Bray, R. H., and Kurtz, L. T. Determination of total, organic, and available forms of phosphorus in soils. *Soil Sci.* 59: 30-45. 1945.

³ Hill, W. L.; Fox, E. J., and Mullins, J. F. Preparation of radioactive phosphate fertilizers for plant-utilization tests by tracer methods. *Indus. and Engin. Chem.* 41: 1328-1334. 1949.

posited to three for measurement of P^{32} and for analysis of total P. Poor growth limited the number of alfalfa samplings that could be taken on the Webster soil of pH 6.7 and on the Clarion soil.

RESULTS

Oat and alfalfa yields

The yield data for the oats are given in table 1. The oat data show that significant responses at the different sampling dates usually occurred from the use of phosphate. There is little evidence, however, of differential response between sources of phosphorus. Significant increases in the grain yield from phosphorus were obtained only on the Webster soil of pH 6.0.

TABLE 1

*Effect of different sources of phosphate on yield of oat plants at different stages of growth and on final grain yield**

SOURCE OF PHOSPHATE	WEBSTER SILTY CLAY LOAM, pH 6.0				WEBSTER SILTY CLAY LOAM, pH 6.7				CLARION LOAM, pH 5.6			
	Dry matter†			Grain	Dry matter†			Grain	Dry matter†			Grain
	6/2	6/16	7/3		6/8	6/17	7/15		6/3	6/15	7/9	
None.....	417	1372	3828	66.7	646	1389	4022	49.5	399	1141	3211	58.2
Dicalcium phosphate (2594b).	550	1777	4848	81.9	827	1511	3190	48.2	477	1411	3352	61.2
Alpha tricalcium phosphate (2595b).....	608	1753	4678	82.8	723	1580	3616	53.2	455	1207	3337	60.8
Superphosphate.....	615	1683	4780	82.8	770	1607	4066	51.3	495	1319	3516	59.8
Calcium metaphosphate (2596b).....	545	1795	4528	84.9	723	1524	3672	52.7	464	1293	3369	57.7
L.S.D. (.05).....	82	219	652	7.3	129	226	580	N.S.	49	122	N.S.	N.S.

* Yields of dry matter expressed as pounds per acre. Grain yields are in bushels per acre.

† On sampling dates shown. Phosphate application and seeding dates were April 20, on the Clarion soil and the Webster soil of pH 6.0, and April 28, on Webster of pH 6.7. Approximate stages of growth at time of sampling: 1st sample—7 to 10 inches; 2nd sample—boot stage; 3rd sample—dough stage.

In every case where estimates of alfalfa yield were possible, a significant response to phosphorus was obtained, but in no instance were differences between phosphates significant.

Insufficient moisture during the growing period greatly retarded growth on the Webster soil of pH 6.7 and on the Clarion soil. The Webster of pH 6.0 showed only occasional evidences of moisture deficiency.

Utilization of fertilizer phosphorus

Oats. On both Webster soils, the proportion of phosphorus in the plant from superphosphate usually was greater than that derived from the other sources, as shown in table 2. This trend was particularly evident on the Webster soil of pH 6.7. On the Webster soil of pH 6.0, superphosphate was slightly but not signifi-

cantly better than dicalcium or tricalcium phosphate on the last sampling date. On the most acid soil (Clarion, pH 5.6), superphosphate appeared to be the best source of phosphorus during the first period of growth. At the later samplings its superiority over the tricalcium phosphate tended to disappear. There is a possibility that a high fixation of the phosphorus from superphosphate occurred at pH 5.6, thus accounting in part for the phosphorus' becoming relatively less

TABLE 2

Percentage of the plant phosphorus derived from fertilizer and percentage recovery of applied phosphorus in relation to source of phosphate and stage of growth of oats

SOURCE OF PHOSPHATE	PERCENTAGE P DERIVED FROM FERTILIZER			PERCENTAGE RECOVERY OF APPLIED P		
	1*	2	3	1	2	3
<i>Webster silty clay loam (pH 6)</i>						
No phosphate	—	—	—	—	—	—
Dicalcium phosphate	22.3	23.5	32.5	1.7	4.6	18.0
Alpha tricalcium phosphate	26.3	23.3	32.1	2.1	4.7	18.0
Superphosphate	40.7	33.6	39.1	3.3	6.8	22.4
Calcium metaphosphate	18.7	17.1	25.9	1.3	3.7	14.1
L.S.D. (.05)	19.3	6.2	9.8			
<i>Webster silty clay loam (pH 6.7)</i>						
No phosphate	—	—	—	—	—	—
Dicalcium phosphate	5.1	4.2	4.9	0.7	0.9	1.8
Alpha tricalcium phosphate	2.5	3.2	5.3	0.3	0.7	2.3
Superphosphate	10.3	10.9	20.0	1.5	2.6	10.3
Calcium metaphosphate	3.6	4.2	9.8	0.5	0.9	4.5
L.S.D. (.05)	4.5	4.5	7.0			
<i>Clarion loam (pH 5.6)</i>						
No phosphate	—	—	—	—	—	—
Dicalcium phosphate	14.9	12.3	14.8	0.9	1.9	6.8
Alpha tricalcium phosphate	18.7	14.2	22.3	1.1	2.1	8.9
Superphosphate	26.5	15.4	22.5	1.7	2.3	10.4
Calcium metaphosphate	13.0	8.0	12.2	0.8	1.2	5.0
L.S.D. (.05)	10.8	7.2	6.5			

* Sampling. Dates of 1st, 2nd, and 3rd samplings are given in footnote †, table 1.

available with time. On the Webster soil of pH 6.0 and the Clarion of pH 5.6, calcium metaphosphate was a less efficient source of phosphorus to the plant than either dicalcium or alpha tricalcium phosphate.

Extremely low values for the percentage of phosphorus derived from the fertilizers were obtained on the Webster of pH 6.7, probably largely attributable to lack of sufficient moisture. Here the plants derived two to four times as much phosphorus from the superphosphate as from the other sources.

Percentage recovery of phosphorus from the different sources also is shown in table 2. On all soils, greatest recovery was from superphosphate. On the Webster soils, dicalcium and alpha tricalcium phosphates were intermediate, and lowest recovery was from the metaphosphate. On the soil of pH 6.7, however, about the same recovery was obtained from the metaphosphate as from dicalcium or tricalcium phosphate except on the last sampling date.

Alfalfa. The values for percentage of phosphorus derived from the fertilizers by alfalfa in relation to sampling dates are shown in table 3. More phosphorus was absorbed from the superphosphate than from the other sources on the Webster of pH 6.7. The uptake of fertilizer phosphorus was low, however, probably partly because of lack of moisture. On the Clarion soil the amount of phosphorus derived from the dicalcium phosphate appeared to be significantly less than from the other sources. The relatively low absorption of fertilizer phosphorus and poor growth on the Webster of pH 6.7 and the Clarion would indicate that the factors

TABLE 3

Percentage of phosphorus in alfalfa derived from fertilizer in relation to stage of growth and source of phosphorus

SOURCE OF PHOSPHATE	PERCENTAGE P DERIVED FROM FERTILIZER					
	Webster pH 6.0			Webster pH 6.7		Clarion pH 5.6
	July 3	Aug. 9	Sept. 6	July 15	Sept. 6	Sept. 6
Dicalcium phosphate	36.3	52.8	37.3	7.9	4.7	8.4
Alpha tricalcium phosphate	33.7	45.2	32.9	7.4	6.4	13.9
Superphosphate	42.3	76.6	35.9	17.7	12.7	15.4
Calcium metaphosphate	48.3	46.4	22.6	8.8	6.7	13.0
L.S.D.	11.1	28.6	12.7	6.8	5.5	3.9

which restricted growth also inhibited absorption of phosphorus from the fertilizers. On the other hand, plants obtained a high proportion of their phosphorus from the fertilizer on the Webster soil of pH 6.0. In the latter case, the relative amounts of phosphorus absorbed from the different fertilizers differed with each sampling.

The percentage recovery of applied phosphorus was considerably lower for alfalfa than for oats. The ranges in percentage recovery for the Webster of pH 6.0 were as follows: July 3, 1.8–3.0; August 9, 3.8–4.4; September 3, 5.3–6.3. The recovery values calculated for the only alfalfa samples taken from the Clarion plots ranged from 0.6 to 1.0 per cent.

SUMMARY AND CONCLUSIONS

Three experiments were conducted in Iowa on Clarion loam of pH 5.6 and on two Webster silty clay loam soils of pH 6.0 and pH 6.7 to determine the relative effectiveness of four different phosphate fertilizers as sources of phosphorus to

oats and alfalfa. Yields of dry matter at various stages of growth and grain yields at harvest gave no indication of a differential response to sources.

Tracer studies with P^{32} revealed that the percentage of phosphorus in the oat plant derived from the fertilizer differed with various phosphate carriers. In every instance, a greater proportion of phosphorus was derived from superphosphate than from any of the other carriers investigated. This superiority of superphosphate was particularly noticeable during early growth, and it persisted to the greatest extent through the growing period on the soil of pH 6.7. Calcium metaphosphate tended to supply less phosphorus on soils of pH 5.6 and 6.0 than did the other carriers. Calcium metaphosphate was somewhat superior, however, to dicalcium and alpha tricalcium phosphate on the soil of pH 6.7. The data suggest that the oats utilized the phosphorus in dicalcium and alpha tricalcium phosphates to the greatest advantage on the soils of pH 5.6 and 6.0.

Young alfalfa generally derived a greater proportion of phosphorus from superphosphate than from the other carriers. No significant differences generally existed between the amounts of phosphorus derived from dicalcium phosphate, alpha tricalcium phosphate, and calcium metaphosphate on soils of pH 6.0 and 6.7. Dicalcium phosphate was significantly inferior to alpha tricalcium and metaphosphate on the soil of pH 5.6.

UTILIZATION OF PHOSPHORUS FROM VARIOUS FERTILIZER MATERIALS: IV. SUGAR BEETS, WHEAT, AND BARLEY IN COLORADO¹

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Interest in the phosphate fertilization problems of western soils has increased greatly during the last several years. Radioactive phosphorus provides a new research tool having unique value for application to these problems. Phosphate fertilizers containing a very small amount of radiophosphorus have been used in field and greenhouse studies to estimate the amount of phosphorus in a plant which is derived from the fertilizer (1, 3, 4, 5, 6). The effect of source of phosphorus, placement, and crop species on the utilization of phosphorus applied to a calcareous soil are reported in this paper.

MATERIALS AND METHODS

Two experiments were conducted on Fort Collins loam (Agronomy Farm) and one on Cass fine sandy loam (Hoffman Farm). Both soils are calcareous, containing approximately 2.5 per cent CaCO_3 in the surface 8 inches.

A factorial experimental design including placement and source of phosphorus was used for sugar beets, wheat, and barley on the Agronomy Farm. The placements were (a) phosphorus mixed with a rotiller in a band 4 inches wide and 4 inches deep (2 inches versus 4 inches deep on wheat and barley) and (b) phosphorus placed in a single band 4 inches deep and 4 or 5 inches to one side of the row on beets only. The phosphate materials were superphosphate, calcium metaphosphate (2596b), dicalcium phosphate (2594b), and alpha tricalcium phosphate (2595b). These materials as identified by sample number are described by Hill *et al.* (2). Nitrogen was applied at the rate of 60 pounds per acre. There were three replications.

On the Hoffman Farm the same materials were used on sugar beets, but only the band placement. There were six replications. Nitrogen was not applied, since the previous crop was alfalfa.

Phosphorus was applied at the rate of 40 pounds P_2O_5 per acre on all experiments.

Each sugar beet plot was eight rows wide and 64 feet long. Three rows 32 feet long were treated with radioactive phosphate fertilizer. The wheat and barley plots were 41 feet long and six rows wide (barley and wheat planted in alternate rows). One row of each crop 17 feet long was treated with radioactive phosphate fertilizer. Nonradioactive phosphate was applied to the remaining rows at the same rate as the radioactive phosphate.

The activity of the radioactive materials was about 0.1 millicurie per gram of P_2O_5 at planting time.

¹ Report of a study made under the Research and Marketing Act of 1946. Joint contribution: Colorado Scientific Series 308. The work was supported in part by a grant from the Industry Phosphate Research Committee and the Tennessee Valley Authority.

The dates of field operations are shown in table 1.

Forty to fifty sugar beet leaves were taken for analysis. At the first sampling, sixty heads were taken for barley and wheat, and the grain was used for the second sampling.

The sugar beets were irrigated five times during the season at each location. The irrigation dates were July 6, July 16, July 29, August 19, and September 4 on the Agronomy Farm. The dates on the Hoffman Farm varied only a few days from those on the Agronomy Farm. The wheat and barley were irrigated once on July 9.

TABLE 1
Dates of field operations

LOCATIONS	DATE OF PLANTING	SAMPLING DATE*			
		1	2	3	4
Sugar beets					
Agronomy Farm	April 24	May 28	June 24	August 2	Sept. 13
Hoffman Farm	April 27	May 29	June 30	August 10	Sept. 14
Wheat					
Agronomy Farm	May 3	July 9	August 2		
Barley					
Agronomy Farm	May 3	July 9	July 29		

* The sampling dates correspond to the following stages of growth:

Sugar beets:

1. Third pair of leaves out; thinning time.
2. Beginning of grand period of growth.
3. Middle of grand period of growth.
4. Near harvest time.

Wheat and barley:

1. Early dough stage.
2. Harvest.

All fertilizers were applied with a four-row belt-type placement machine mounted on a John Deere tractor. The fertilizer shoes or the rotiller could be attached to the tractor.

RESULTS AND DISCUSSION

Sugar beets

The uptake of phosphorus by sugar beets from the various fertilizers in relation to placement is shown in figure 1. The values for least significant difference apply only to the interaction of placement and source of material. Evidently, the roots had not penetrated to the locality of the band of fertilizer at the first sampling date. The seeds were planted in the rotiller band; therefore, the roots could con-

tact the fertilizer from the start in this case. This comparison of early uptake from the fertilizer may be very important on soils of low available phosphorus. It is commonly known, for example, that seedling beets are more likely to be injured by a "root rot" or "damping off" disease on soils low in available phosphorus. These data suggest the advisability of placing at least part of the phosphate on such soils in a position where it could be reached by the young seedling roots.

Uptake of phosphorus from superphosphate is approximately twice as much from the band placement as from the rotiller at all remaining sampling periods. The uptake from calcium metaphosphate follows roughly the same pattern, except for the second sampling date. Hydrolysis of the metaphosphate to orthophosphate was probably slow up to this time, since the plots were not irrigated until after the second sampling period. The plants absorbed more phosphorus from dicalcium phosphate in the rotiller placement at all sampling periods.

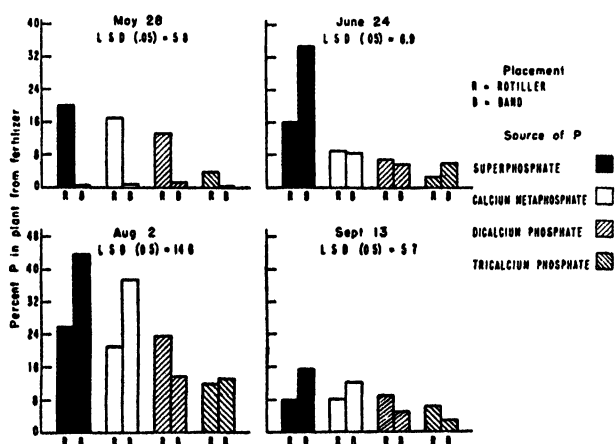


FIG. 1. EFFECT OF PLACEMENT AND SOURCE OF PHOSPHORUS ON PERCENTAGE OF PHOSPHORUS IN SUGAR BEETS DERIVED FROM FERTILIZER ON FORT COLLINS LOAM

Placement seemed to have little effect on the utilization of phosphorus from alpha tricalcium phosphate.

There is an interaction between type of phosphate and placement at each sampling date. The superphosphate showed greater uptake from the band placement (except for first sample), whereas dicalcium phosphate showed greater uptake from the rotiller placement. Calcium metaphosphate showed greater uptake from the band also at the last two sampling periods and the interaction with dicalcium phosphate is significant. The effect of placement on alpha tricalcium phosphate varies slightly with sampling period, but this material also shows the interaction with the more soluble sources of phosphorus. The rotiller placement may permit greater contact of the roots with the fertilizer, and with the dicalcium phosphate the amount of root-fertilizer contact appears to be an important factor affecting uptake. Some of the fertilizer mixed by the rotiller will probably be in soil dry enough to impair root activity during certain growth periods compared

to the band placement. This condition may explain in part the lower uptake of phosphorus from superphosphate and calcium metaphosphate in the rotiller placement. The other two materials were probably affected in a similar manner, but other factors were predominant. If reversion of soluble phosphates to less soluble materials is a factor affecting uptake of phosphorus on this soil, then the rotiller placement would be expected to favor greater reversion than the band placement, resulting in a lower uptake of phosphorus.

The early uptake of phosphorus (second sampling) from the band placement shows some striking differences among the various fertilizers. Superphosphate supplied four to five times as much phosphorus to the plant as the other materials,

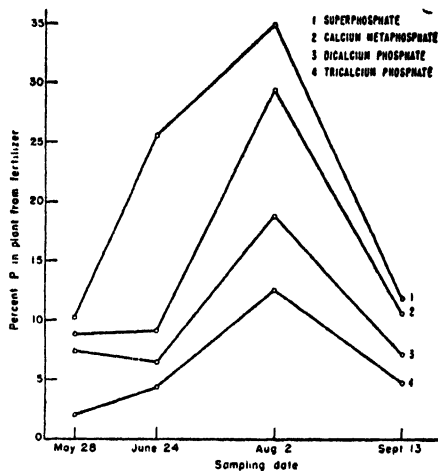


FIG. 2

FIG. 2. PERCENTAGE OF PHOSPHORUS DERIVED FROM FERTILIZER AS AFFECTED BY SOURCE OF PHOSPHORUS ON FORT COLLINS LOAM

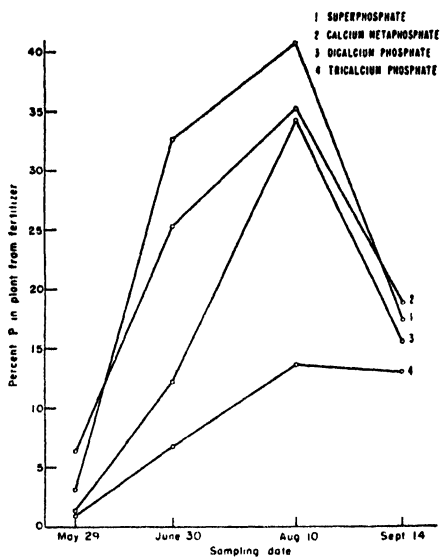


FIG. 3

FIG. 3. PERCENTAGE OF PHOSPHORUS IN SUGAR BEETS DERIVED FROM FERTILIZER AS AFFECTED BY SOURCE OF PHOSPHORUS ON CASS FINE SANDY LOAM

whereas at later samplings the differences are much less. It is well known that when crops do respond to phosphate applications, the most marked differences occur in the early stages of growth before the root system becomes well established. The ability of superphosphate to furnish larger amounts of phosphorus to the plants in the early stages of growth may explain its usual superiority over these other materials.

The average uptake of phosphorus from both placements as related to source of phosphorus is shown in figure 2. Absorption of phosphorus from the fertilizer was highest from superphosphate and least from alpha tricalcium phosphate. A similar relationship is indicated in figure 3 for Cass fine sandy loam. Superphosphate was significantly better than calcium metaphosphate only for the second sampling period.

Final yields of sugar beets for each location are shown in table 2. No response to the fertilizer was found on the Agronomy Farm, and the high level of yield indicates a plentiful supply of available phosphorus in this field. The yield responses on the Hoffman Farm were with the two fertilizers showing the greatest uptake of phosphorus from the fertilizer.

Analysis of the leaves for total phosphorus showed that the phosphorus content was increased significantly over the check plots by superphosphate and calcium metaphosphate at the last three sampling dates on both locations.

TABLE 2
Effect of source of phosphorus on yield of sugar beets

TREATMENT	AGRONOMY FARM	HOFFMAN FARM
	ton/A.	ton/A.
None	19.9	13.2
Superphosphate	20.7	16.7**
Calcium metaphosphate	20.2	15.1*
Dicalcium phosphate	20.3	14.3
Alpha tricalcium phosphate	20.6	14.1

* Significant at 5 per cent level.

** Significant at 1 per cent level.

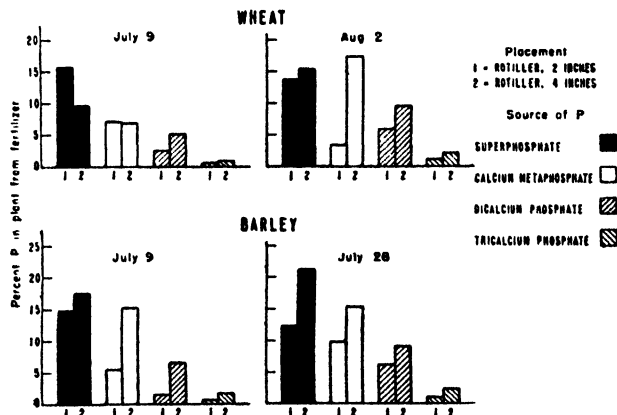


FIG. 4. EFFECT OF SOURCE OF PHOSPHORUS AND PLACEMENT ON PERCENTAGE OF PHOSPHORUS IN WHEAT AND BARLEY DERIVED FROM FERTILIZER ON FORT COLLINS LOAM

Wheat and barley

Effects of source of material and placement on the uptake of applied phosphorus by wheat and barley are shown in figure 4. In this experiment the placements (2 and 4 inches) were obtained by varying the depth of the rotiller. There is no interaction between source of phosphate and placement. The deeper placement produced greater absorption of phosphorus from the fertilizers, except with superphosphate on wheat at the first sampling. The plants absorbed the most phosphorus from superphosphate and the least from alpha tricalcium phosphate,

as shown by the average values for both placements in figure 5. The plots were irrigated between the two sampling periods.

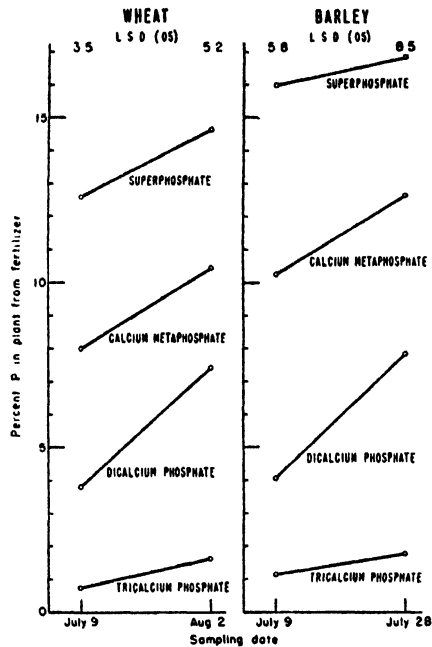


FIG. 5. PERCENTAGE OF PHOSPHORUS IN WHEAT AND BARLEY DERIVED FROM VARIOUS FERTILIZERS ON FORT COLLINS LOAM

TABLE 3

Effect of source of phosphorus and placement on yields of barley and wheat

TREATMENT	WHEAT	BARLEY
	<i>bu./A.</i>	<i>bu./A.</i>
Superphosphate.....	24.1*	57.6
Calcium metaphosphate.....	24.0*	57.4
Dicalcium phosphate.....	23.2	52.2
Alpha tricalcium phosphate.....	21.3	52.9
None.....	21.9	53.7
Rotiller, 2-inch depth.....	22.4	53.5
Rotiller, 4-inch depth.....	23.4	55.5

* Significant at 5 per cent level.

A significant increase in yield of wheat, as shown in table 3, was obtained from superphosphate and calcium metaphosphate, but the increases with these two fertilizers on barley were just under the 5 per cent level of significance. These same two fertilizers produced a significant increase in the phosphorus content of the grain.

SUMMARY

Field experiments were conducted on calcareous soils to determine the effect of source of material, placement, and crop species on the uptake of phosphorus from the fertilizer.

Superphosphate supplied the largest amounts of phosphorus to the plants, and alpha tricalcium phosphate furnished the least. Calcium metaphosphate and dicalcium phosphate were intermediate.

During the early stages of growth, the uptake of phosphorus from superphosphate was significantly greater than from each of the other materials.

There was an interaction between source of material and placement on the sugar beets. The more soluble phosphates, superphosphate and calcium metaphosphate, showed a greater uptake from the band placement, whereas the less soluble phosphates were more available in the rotiller placement.

Sugar beets and wheat showed yield responses to superphosphate and calcium metaphosphate.

Deeper placement of the fertilizer was, in general, superior to a more shallow placement.

REFERENCES

- (1) DEAN, L. A., ET AL. 1948 Application of tracer technique to studies of phosphatic fertilizer utilization by crops: I. *Soil Sci. Soc. Amer. Proc.* (1947) **12**: 107-112.
- (2) HILL, W. L., FOX, E. J., AND MULLINS, J. F. 1949 Preparation of radioactive phosphate fertilizers for plant-utilization tests by tracer methods. *Indus. and Engin. Chem.* **41**: 1328-1334.
- (3) NELSON, W. L., ET AL. 1948 Application of tracer technique to studies of phosphatic fertilizer utilization by crops: II. *Soil Sci. Amer. Proc.* (1947) **12**: 113-118.
- (4) SPINKS, J. W. T., AND BARBER, S. A. 1947 Studies of fertilizer uptake using radioactive phosphorus. *Sci. Agr.* **27**: 145-146.
- (5) SPINKS, J. W. T., AND BARBER, S. A. 1948 Studies of fertilizer uptake using radioactive phosphorus: II. *Sci. Agr.* **28**: 79-87.
- (6) ULRICH, A. U., JACOBSEN, L., AND OVERSTREET, R. 1947 Use of radioactive phosphorus in a study of the availability of phosphorus to grape vines under field conditions. *Soil Sci.* **64**: 17-28.

A COMPARISON OF PHOSPHORUS UTILIZATION BY CROPS¹

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Two levels of soil phosphorus were used to compare the utilization of soil and applied phosphorus by crops. Corn and cotton were grown on Norfolk sandy loam and corn, potatoes, and soybeans on Bladen silt loam. Similar weather conditions prevailed at all locations.

The objective of this paper is to compare the utilization of phosphorus by crops as related to the level of soil phosphorus and the rate of applied phosphorus.

MATERIALS AND METHODS

The phosphorus levels at the two locations on Norfolk sandy loam are given in table 1. The rate of application of superphosphate was 50 pounds of P_2O_5 per acre for each crop.

The phosphorus status at the two locations on Bladen silt loam are also shown in table 1. Superphosphate at 25 and 100 pounds P_2O_5 per acre was applied in these experiments.

In each case the phosphorus was placed in bands 3 inches to each side and 2 inches below the seed with a two-row Iron Age belt-type fertilizer distributor and planter. The plot design and sampling procedure was the same as has been described for corn and cotton² and for potatoes³. The schedule of field operations is given in table 2.

RESULTS AND DISCUSSION

Percentage of phosphorus in plant derived from fertilizer

Corn, potatoes, and soybeans. The percentage of the phosphorus in the corn and soybean plants derived from the fertilizer was similar, but strikingly different in the potato plant (fig. 1). The potato plant derived about 60 per cent of its phosphorus from the fertilizer throughout the growing season. The percentage of phosphorus from the fertilizer in the corn and soybean plants was high at the first sampling but decreased progressively throughout the growing season.

The difference in phosphorus absorption between potatoes and corn may be related to the nature of root extension and length of growing season. Potatoes are a short-season, rapid-growing crop that has a limited root system and appears to depend heavily on a concentrated supply of fertilizer phosphorus. This was indicated by response on soils of high-phosphorus levels⁴. Corn is a long-season crop

¹ Joint contribution: North Carolina Journal Series Paper 312. This work was supported in part by a grant from the Industry Phosphate Research Committee.

² Nelson, W. L., et al. Utilization of phosphorus as affected by placement: II. This issue *Soil Sci.*

³ Jacob, W. C., et al. Utilization of phosphorus by potatoes. This issue *Soil Sci.*

⁴ Cummings, R. W., Peech, M., and Hawkins, A. Nutrient status of soils in commercial potato producing areas of the Atlantic and Gulf Coast: I, II, III. *Soil Sci. Soc. Amer. Proc.* (1945) 10: 240-256. 1946.

TABLE 1
Analyses of soils

	FIELD 1 (Low-soil phosphorus)		FIELD 2 (High-soil phosphorus)	
	pH	P ₂ O ₅ *	pH	P ₂ O ₅ *
		lb./A.		lb./A.
Norfolk sandy loam				
Corn.....	5.2	49	5.5	312
Cotton.....	5.5	67	5.5	288
Bladen silt loam				
Corn.....	5.3	65	5.5	151
Soybeans.....	5.3	81	5.4	175
Potatoes.....	5.3	66	5.6	240

* Soluble in 0.002 N H₂SO₄.

TABLE 2
Schedule of field operations

	CORN			COTTON		
	Date		Stage of growth	Date		Stage of growth
	1	2		1	2	
Norfolk sandy loam						
Planting date.	April 23	April 23		April 17	April 16	
Sampling						
1.....	May 14	May 10	2-3 inches high	May 14	—	Cotyledon stage
2.....	May 24	May 17	5-7 inches high	May 28	May 22	One pair of true leaves
3.....	June 1	May 24	10-20 inches high	July 8	June 22	First squares
4.....	June 14	June 7	18-20 inches high	Aug. 9	Aug. 9	Half of bolls full size
5.....	June 28	June 28	34-36 inches high			
6.....	Aug. 17	Aug. 10	Late roasting ear			

	CORN		SOYBEANS		POTATOES	
	Date	Stage of growth	Date	Stage of growth	Date	Stage of growth
Bladen silt loam						
Planting date.	April 29		April 28		March 18	
Sampling						
1.....	May 31	5-7 inches high	May 25	2nd trifoliates	April 19	6-8 inches high
2.....	June 24	34-36 inches high	June 17	12-15 inches tall	April 30	12-14 inches high
3.....	Aug. 11	Late roasting ear	July 13	Early bloom stage	May 12	Early bloom
4.....			Aug. 17	Early pod	June 9	Before leaves matured

that has a very extensive root system and hence may absorb a relatively large amount of soil phosphorus during the late stages of growth.

In the initial stages of growth, the soybean plant derived a much lower percentage of its phosphorus from the fertilizer than did corn. At the later samplings, the curves were very similar (fig. 1). The plant weight of corn was increased about two and one-half times by the application of phosphorus in both the high- and low-level soils at the time of the first sampling. During this same period of growth, the soybean plant weight was increased only about 25 per cent. The pronounced early vegetative response of corn to phosphorus is probably related to its effective utilization of fertilizer phosphorus in the initial stages of growth.

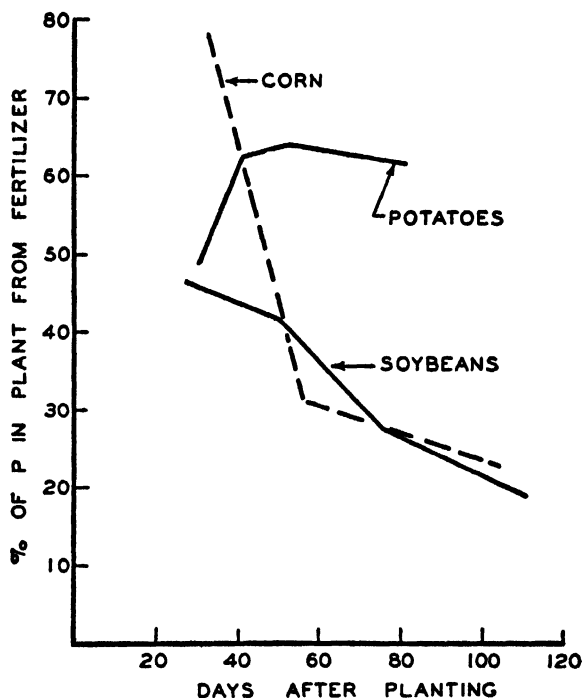


FIG. 1. PERCENTAGE OF THE PHOSPHORUS IN CORN, SOYBEANS, AND POTATO PLANTS DERIVED FROM FERTILIZER AT THE HIGH LEVEL OF SOIL PHOSPHORUS IN BLADEN SILT LOAM

The rate of application was 100 pounds of P_2O_5 per acre.

The curves for the 25-pound per acre rate of application were similar to those for the 100-pound rate shown in figure 1 but displaced at a lower level. The curves for the low-phosphorus soil were similar to those for the high-phosphorus soil but displaced at a somewhat higher level.

Corn and cotton. The percentages of the phosphorus in the corn and cotton plants derived from the fertilizer were similar at the low and high levels of soil phosphorus (fig. 2). Although the shapes of the curves are very similar, the curve for cotton is displaced to the right of the corn in the early stage of development. This is a reflection of the characteristic slow, early growth of the cotton plant.

At the first sampling, only a small percentage of the phosphorus in the two crop

plants was derived from the fertilizer. It is believed that many of the plant roots had not yet reached the fertilizer band, and the plant was dependent mainly on the phosphorus supply in the seed. The calculated phosphorus content of the seed at the first sampling is great enough to account for the phosphorus in the plants not derived from the fertilizer.

The curves for the low-phosphorus soil were markedly different from those for the high-phosphorus soil, the percentage of phosphorus in the plants from the fertilizer being higher in the low-phosphorus soil throughout the season.

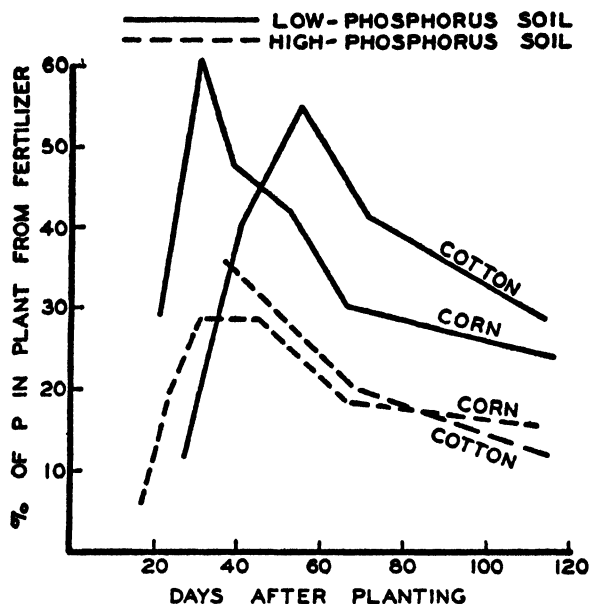


FIG. 2. PERCENTAGE OF THE PHOSPHORUS IN CORN AND COTTON PLANTS DERIVED FROM FERTILIZER AT LOW AND HIGH LEVELS OF SOIL PHOSPHORUS IN NORFOLK SANDY LOAM

The rate of application was 50 pounds of P_2O_5 per acre.

Amount of P_2O_5 absorbed from fertilizer and soil

Corn, potatoes, and soybeans. Potatoes absorbed the most fertilizer phosphorus and soybeans the least (table 3). This was true at all rates of application and levels of phosphorus in the soil.

When the total amount of P_2O_5 in the plants is considered, however, potatoes always had the lowest amount and corn the highest (table 3). Corn, of course, has the largest amount of dry matter per acre and potatoes the least. The percentage of P_2O_5 in the plant was lower in the corn than in the potatoes and soybeans (table 5).

* The uptake of fertilizer and soil phosphorus by soybeans at the four sampling dates is shown in figure 3.

The corn and the soybean plants absorb the bulk of their phosphorus late in the season after the root system is about fully extended. This fact helps explain why the level of soil phosphorus appears to be important in determining the

TABLE 3

Phosphorus in the plant from the fertilizer, percentage fertilizer phosphorus used, and total phosphorus in the plant as related to level of soil phosphorus and rate of applied phosphorus at last sampling

CROP	P ₂ O ₅ * IN SOIL	25 POUNDS P ₂ O ₅ APPLIED			100 POUNDS P ₂ O ₅ APPLIED		
		P ₂ O ₅ in plant from fertilizer	Percentage of fertilizer P ₂ O ₅ used	Total P ₂ O ₅ in plant	P ₂ O ₅ in plant from fertilizer	Percentage of fertilizer P ₂ O ₅ used	Total P ₂ O ₅ in plant
	lb./A.	lb./A.		lb./A.	lb./A.		lb./A.
<i>Bladen</i>							
Corn	65	3.8	15.2	23.0	10.1	10.1	30.0
	151	3.2	12.9	40.1	9.0	9.0	40.0
Soybeans	81	2.6	10.4	25.7	7.8	7.8	28.2
	175	1.4	5.6	31.8	6.4	6.4	33.8
Potatoes	66	6.8	27.2	16.2	12.6	12.6	20.0
	240	4.6	18.4	18.0	14.5	14.5	24.0
<i>Norfolk</i>							
Corn	49	5.2	10.4	21.8			
	312	7.1	14.2	46.8			
Cotton	67	1.8	3.6	6.8			
	288	1.9	3.8	17.7			

* Soluble in 0.002 N H₂SO₄.

TABLE 4

Final yields of corn, cotton, potatoes, and soybeans as influenced by levels of soil phosphorus and rates of phosphate fertilization

APPLIED P ₂ O ₅	FIELD 1 (LOW SOIL PHOSPHORUS)			FIELD 2 (HIGH SOIL PHOSPHORUS)		
	Corn	Soybeans	Potatoes	Corn	Soybeans	Potatoes
lb./A.	bu./A.	bu./A.	cwt./A.	bu./A.	bu./A.	cwt./A.
<i>Bladen</i>						
0	84.0	30.2	76.0	121.1	28.3	200.2
25	98.3	32.1	133.5	131.0	29.7	219.4
100	102.2	34.8	157.0	129.2	30.3	233.0
L.S.D. (.05).....	N.S.	3.2	18.2	N.S.	N.S.	20.9
C. V. (%).....	15	8	11	7	8	8
	Corn	Seed cotton		Corn	Seed cotton	
	bu./A.	lb./A.		bu./A.	lb./A.	
<i>Norfolk</i>						
0	66.1	834		91.7	2049	
50	66.1	1403		91.4	2058	
L.S.D. (.05).....	N.S.	454		N.S.	N.S.	
C. V. (%).....	8	29		16	17	

phosphorus composition and the total uptake by these plants. This late absorption is further substantiated by the fact that at harvest the total phosphorus

TABLE 5

Comparison of percentages of P_2O_5 in four crops as affected by phosphorus level of two soils at three sampling periods

GROWTH PERIOD*	NORFOLK SANDY LOAM				BLADEN SILT LOAM					
	50 pounds P_2O_5 applied				100 pounds P_2O_5 applied					
	Cotton		Corn		Corn		Potatoes		Soybeans	
	Low†	High†	Low	High	Low	High	Low	High	Low	High
	per cent	per cent	per cent	per cent	per cent	per cent	per cent	per cent	per cent	per cent
1.....	.79	.85	.61	1.01	.61	.64	.88	1.05	.86	.84
2.....	.55	.76	.43	0.63	.53	.58	.55	0.75	.56	.63
3.....	.58	.79	.30	0.46	.27	.31	.56	0.50	.53	.58

* The periods were selected on the basis of comparable stages of growth.

† Soil phosphorus level.

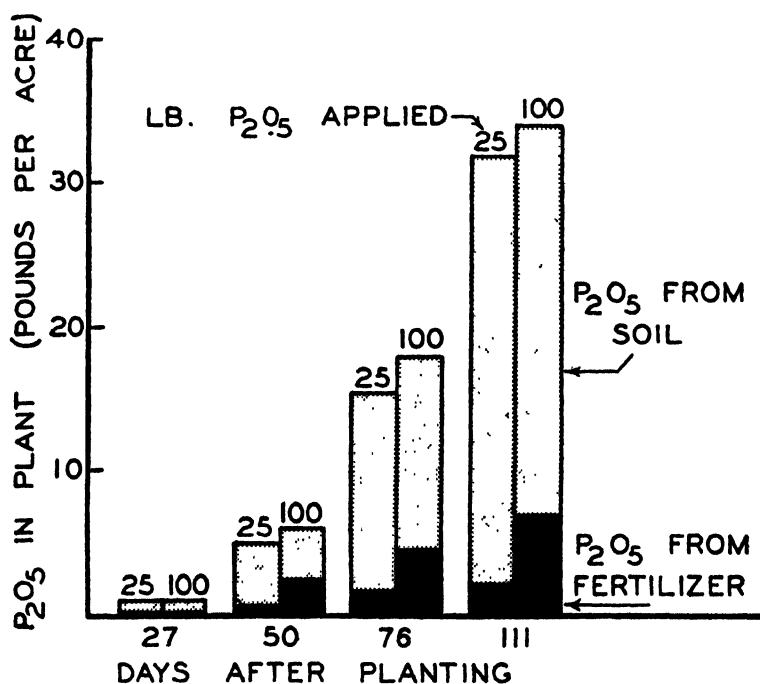


FIG. 3. TOTAL P_2O_5 UPTAKE FROM FERTILIZER AND SOIL PHOSPHORUS BY SOYBEANS ON BLADEN SILT LOAM CONTAINING 175 POUNDS OF SOIL P_2O_5

content of the corn grain alone was higher than that of the total plant at the last sampling date.

Corn and cotton. Corn absorbed approximately twice as much fertilizer phosphorus as cotton at the Norfolk locations. This occurred at all rates of applied phosphorus and levels of phosphorus in the soil (table 3).

Corn had more than twice as much total P_2O_5 in the plants as did cotton at the 50-pound rate of P_2O_5 (table 3). This is a reflection of the differences in the amount of dry matter at the last sampling, since the percentage of P_2O_5 in the plant was higher in the cotton than in the corn (table 5).

Comparison of the total amount of P_2O_5 in the two crops as affected by level of soil phosphorus showed a much greater increase in total pounds of P_2O_5 in the corn due to level of soil phosphorus.

Yields

Corn, potatoes, and soybeans. Phosphorus applications on the Bladen series increased the yield of potatoes at both locations and the yield of soybeans on the low-phosphorus soil (table 4). Corn showed a marked early growth response to phosphorus, but there was no effect on final yields. A possible explanation of this difference is the long growing season for corn in North Carolina. Under these conditions the plants on the no-phosphorus plots had ample time to overcome early growth differences.

Corn and cotton. Cotton gave an early growth response to applications of phosphorus on the low-phosphorus soil, and this was reflected in the final yield (table 4). Cotton is subject to insect damage on the developing squares and young bolls. Hence, rapid early development is considered to be essential in cotton production.

Corn on the Norfolk series gave no yield response to phosphorus application, but the growth response was similar to that noted at the Bladen locations.

SUMMARY

A comparison of the utilization of phosphorus by corn, potatoes, and soybeans was made on a low- and a high-phosphorus Bladen soil. Corn and cotton were similarly compared on the Norfolk series.

Corn, potatoes, and soybeans varied greatly in the percentage of phosphorus derived from the fertilizer. Although the percentage for corn was highest at the first sampling, the percentages for both corn and soybeans decreased sharply during the season. Potatoes absorbed a relatively high proportion of fertilizer phosphorus throughout the growing season.

Corn and cotton were similar in proportion of phosphorus absorbed from the fertilizer at high and low soil phosphorus levels.

Comparison of potatoes, corn, and soybeans showed that potatoes absorbed the most fertilizer phosphorus and soybeans the least. Corn, however, absorbed the greatest total amount of phosphorus and potatoes the least.

Comparison of corn and cotton showed that corn absorbed the most fertilizer phosphorus and also the greatest total amount of phosphorus.

The percentage P_2O_5 at the last sampling was lower in corn than in any of the other crops. The percentage of P_2O_5 in both corn and cotton was considerably higher on the high-phosphorus soil than on the low-phosphorus soil in the Norfolk series. The effect was less apparent in the Bladen series.

Potatoes gave a yield response on both locations, whereas soybeans gave a yield response only on low-phosphorus soil. Cotton also gave a yield response on low-phosphorus soil.

UTILIZATION BY PLANTS OF PHOSPHORUS IN FARM MANURE: I. LABELING OF PHOSPHORUS IN SHEEP MANURE WITH P^{32}

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In an investigation to determine the utilization by plants of phosphorus in farm manure when applied to soils alone and in conjunction with superphosphate (7), it was necessary to label properly with P^{32} the different inorganic and organic phosphorus compounds present in manure. This paper summarizes the degree of labeling of organic phosphorus fractions in sheep feces as obtained by two different methods.

LABELING OF PHOSPHORUS IN SHEEP MANURE

Two procedures were followed in an attempt to label the organic phosphorus compounds in sheep feces. In one method $KH_2P^*O_4$ was added directly to the forage fed to a wether yearling lamb.² The second method involved incubation of sheep feces with $KH_2P^*O_4$ as well as with superphosphate containing P^{32} at 37°C. for 22 days.

In the first method the sheep, in an isolated digestion stall, was fed approximately 10 millicuries of P^{32} with the forage daily for 10 days. The forage consisted of chopped ladino-clover-grass mixture that had been dried overnight in an oven at 75°C. One kilogram of this forage was placed daily in a large galvanized can, and a $\frac{3}{8}$ -inch lucite shield with a 2-inch hole in the center was placed over the top of the container. The forage was then sprinkled with 500 ml. of solution containing radioactive phosphorus and mixed well with a shielded, stainless steel hook. This procedure gave fairly uniform mixing without undue personal exposure to radiation from the P^{32} . This P^{32} -treated forage was fed to the animal twice a day. Daily collections of the feces were dried at 75°C. in a continuous forced-draft oven. Apparently there is no significant change in the distribution of organic and inorganic phosphorus under these drying conditions (8). The last 5 days' collections were combined and ground in a portable Wiley mill in an isolated area.

In the second method, involving incubation of the feces with $KH_2P^*O_4$ and radioactive superphosphate, soluble starch equivalent to 1 per cent of the weight of the feces was added as an additional energy source. A third, control, sample of the feces not receiving P^{32} was incubated to ascertain the effect of the intense radiation from P^{32} on microbiological activity as it would influence the distribution of the inorganic and organic phosphorus compounds. The three samples were maintained moist and stirred daily to allow good aeration.

¹ This work was supported in part by a grant from the Industry Phosphate Research Committee.

² The authors thank S. E. Smith of the animal husbandry department for furnishing the sheep used in this investigation.

FRACTIONATION OF PHOSPHORUS IN FARM MANURE

Little work has been reported on the fractionation of phosphorus compounds in manures. Funatsu (1) determined the phospholipid, inorganic + acid-soluble organic, and nucleic acid phosphorus in soybean cake, cotton seed cake, and herring guano. Tsuda (10) and Ghani (2) made similar fractionations and attempted further separation of the inorganic from the organic phosphorus in the acid extract. Peperzak (8) very recently reviewed the literature on the fractionation of manure and presented extensive data on the distribution of the different forms of phosphorus in manure from a number of different animals as well as in manure stored under different conditions.

All the investigations to date reveal a wide variation in the distribution of different phosphorus fractions between different species of animals and even within the same species. Peperzak, in data on the distribution of phosphorus in fresh feces from 18 animals including five different species, reported the following mean percentage values for the different fractions: inorganic 70.6, phytin 5.1, acid-soluble minus phytin 10.7, phospholipid 0.8, and nucleic acid 12.8. But a wide variation was found within any one fraction.

In the present investigation, the primary interest was to determine the extent of labeling of the organic phosphorus in the manure. Thus it was necessary to obtain quantitative separation of the organic phosphorus from the inorganic forms, as well as separation of several organic fractions to ascertain the uniformity of labeling of the organic phosphorus compounds. At the start of this investigation, there was little information on the fractionation of feces, and the methods chosen were based largely on the work of biochemists (9, 11).

To obtain the phospholipid fraction, duplicate 5-gm. samples of the oven-dried materials, ground to pass a 60-mesh screen, were shaken 1 hour with 100 ml. of alcohol-ether mixture (3 parts ethyl alcohol to 1 part diethyl ether) after heating to boiling on a water bath. The suspension was filtered under vacuum, and the residue on the Büchner funnel was washed with three small portions of the 3:1 mixture. This extraction was repeated twice. The combined extracts were evaporated to dryness after addition of 1 ml. of 25 per cent magnesium nitrate, heated to 550°C. for 6 hours, evaporated to dryness with HNO_3 , and reheated to 400°C. for 15 minutes to destroy organic matter. The residue was taken up in concentrated HCl and evaporated to dryness to dehydrate silica. Phosphorus was then determined by the molybdivanadophosphoric acid method (5).

The residue from the alcohol-ether mixture was extracted by shaking with 100 ml. of cold 5 per cent trichloroacetic acid for 1 hour. The suspension was filtered under vacuum and washed three times with small portions of trichloroacetic acid. This extraction was repeated twice. The residue from the acid extraction, containing protein-bound phosphorus, was ashed after addition of magnesium nitrate and phosphorus determined as above.

The trichloroacetic acid extract containing all inorganic phosphorus and such organic phosphorus compounds as are soluble in trichloroacetic acid was divided into two approximately equal volumes. One half was evaporated to dryness, heated at 550°C., and phosphorus determined as before. This fraction contains the inorganic phosphorus plus the acid-soluble organic phosphorus. The other half of the acid extract was shaken for 1 hour with 8 gm. of "Darco G-60" activated carbon and filtered. Previous tests with known amounts of inorganic phosphorus under these conditions showed no adsorption of inorganic phosphorus on the activated carbon. This treatment completely clarifies the extract, which now contains only inorganic phosphorus and a very slight amount of organic phosphorus compounds not ad-

sorbed by carbon. Phosphorus was determined directly on this clarified extract by the molybdivanadophosphoric acid method. The activated carbon containing the adsorbed organic phosphorus compounds was mixed with approximately 1 gm. of CaCO_3 powder; enough water was added to make a slurry and the mixture evaporated to dryness. The carbon was ignited in Vycor crucibles at 700°C . for 12 hours. Phosphorus was then determined in the residue after dehydration of silica.

This fractionation procedure, used on feces containing radioactive phosphorus, was first tried on nonactive feces from the same animal fed on the same forage. In this preliminary test the phosphorus in each of the three successive extracts of the alcohol-ether mixture and the trichloroacetic acid was determined and it was found that the first two extractions with both solvents gave essentially complete separation.

The radioactive phosphorus in the samples was determined by counting from the colored solution (6) following the colorimetric determination. When the spe-

TABLE 1

Distribution of phosphorus in several organic materials and degree of labeling with P^{32} of the phosphorus in three organic fractions

ORGANIC MATERIAL	TOTAL P	TOTAL P, % OF FRACTIONS	INORGANIC P	PHOSPHOLIPID P		PROTEIN-BOUND P		CCl_3COOH -SOLUBLE ORGANIC P	
				Proportion of total phosphorus	Phosphorus in fraction labeled†	Proportion of total phosphorus	Phosphorus in fraction labeled†	Proportion of total phosphorus	Phosphorus in fraction labeled†
	per cent	per cent	per cent	per cent	per cent	per cent	per cent	per cent	per cent
Ladino-clover-grass forage ..	0.32	0.31	67.6	6.55		15.2		8.46	
Feces from sheep fed $\text{KH}_2\text{P}^{32}\text{O}_4$	1.26	1.30	84.3	0.35	83.5 ± 4.2	11.7	89.9 ± 1.1	2.65	86.3 ± 1.7
Sheep feces aged with $\text{KH}_2\text{P}^{32}\text{O}_4$	1.25	1.29	84.9	0.28	93.8 ± 4.0	11.6	47.9 ± 0.4	2.66	43.0 ± 1.1
Sheep feces aged with superphosphate*	2.06	2.13	92.4	0.14	49.8 ± 1.0	5.4	29.5 ± 0.8	1.59	22.3 ± 0.4
Sheep feces aged	1.08	1.12	83.0	0.27		12.8		2.69	
Sheep feces not aged	0.98	0.99	81.5	0.26		12.1		3.10	
Cow feces	0.47	0.47	50.3	0.74		32.5		9.40	

* Indicates phosphorus in material labeled with P^{32} .

† \pm Standard deviation.

cific activity was extremely high, the solution was diluted. For comparison, the forage fed the sheep, sheep feces incubated without addition of phosphorus, sheep feces dried but not incubated, and feces from a cow fed on different forage were carried through the same fractionation procedure. Total phosphorus determinations were made on these samples as a check on the fractionation procedure.

EXPERIMENTAL RESULTS

The results of the fractionation and analysis are listed in table 1. There was approximately 1 per cent phosphorus in the sheep feces dried at 75°C . Of the total phosphorus present, 82 per cent was in the inorganic and 18 per cent in the organic form. The amount of phosphorus in the phospholipid fraction was extremely small, about 0.3 per cent of the total phosphorus in manure; the phosphorus in the acid-soluble organic fraction constituted 3.1 per cent, whereas that

in the protein-bound fraction was 12.1 per cent of the total phosphorus. The clover-grass forage that was fed to the sheep contained slightly more protein-bound phosphorus than the feces, considerably more acid-soluble phosphorus, and very much more phospholipid phosphorus. The inorganic phosphorus content of the cow feces was much lower than that of the sheep feces. Different forage, however, was fed to the cow, and this may account in part for the difference.

The percentage of the phosphorus in the different fractions that was labeled with P^{32} was determined by dividing the specific activity (number of counts per unit time per unit mass of P) of the organic phosphorus fraction by the specific activity of the phosphorus in the inorganic fraction and multiplying the quotient by 100. It is assumed that the phosphorus in the inorganic forms in manure was in isotopic equilibrium before fractionation and hence completely labeled. The labeling of the phosphorus in the inorganic fraction was thus taken as 100 per cent.

The most complete labeling of the phospholipid fraction with P^{32} , 94 per cent, was obtained in the sheep feces aged with $KH_2P^*O_4$. The percentages of phospholipid phosphorus labeled in the sheep feces collected from the animal fed $KH_2P^*O_4$ supplement, and in the sheep feces incubated with radioactive superphosphate were 84 and 50 per cent.

In the protein-bound fraction, this same relationship did not hold. Here much better labeling, 90 per cent, occurred in feeding the animal the $KH_2P^*O_4$ supplement, whereas only 48 and 30 per cent of the phosphorus in this fraction were labeled when feces were incubated with $KH_2P^*O_4$ and with radioactive superphosphate respectively. Similar results were obtained for the acid-soluble organic phosphorus: 86 per cent of the phosphorus in this fraction was labeled as a result of feeding $KH_2P^*O_4$ to the sheep, but only 43 and 22 per cent of the phosphorus were labeled when the feces were incubated with $KH_2P^*O_4$ and with radioactive superphosphate.

DISCUSSION OF RESULTS

Most of the phosphorus in the feces from the sheep fed on ladino-clover-grass forage was in the inorganic form. The protein-bound phosphorus fraction contained most of the organic phosphorus present in manure. The high degree of labeling of the phosphorus in the several organic fractions was apparently effected primarily by microbial decomposition and synthesis, inasmuch as isotopic exchange between the covalently bonded phosphorus in organic compounds in manure and the phosphorus in inorganic forms probably does not occur (3, 4).

The high degree of labeling of the organic forms of phosphorus in the feces obtained by feeding the sheep $KH_2P^*O_4$ with the forage would indicate that decomposition and resynthesis by microorganisms of the organic phosphorus compounds during their passage through the digestive tract of the animal must have occurred very rapidly with approximately equal rates, especially in the protein-bound phosphorus fraction. Possibly a portion of this synthesis may have been caused by the animal, such as the discharge of phospholipids in bile. During the incubation of sheep feces, the decomposition and resynthesis of organic phos-

phorus compounds by microorganisms apparently proceeded much more slowly, and the distribution of phosphorus among the fractions did not change appreciably during the incubation period.

It is realized that the degree of labeling found for a given phosphorus fraction represents the mean value of the degree of labeling of all the organic phosphorus compounds in that fraction. Thus within a given fraction some compounds may be 100 per cent labeled while others may not be labeled at all. This possibility is suggested by the significant differences in the degree of labeling of the three main organic phosphorus fractions obtained upon incubation.

The lower degree of labeling obtained upon incubation of the feces with radioactive superphosphate as compared with $\text{KH}_2\text{P}^*\text{O}_4$ may be attributed to the fact that the superphosphate was added as a finely ground powder whereas the $\text{KH}_2\text{P}^*\text{O}_4$ was added in solution. Thus, failure of some of the particles of superphosphate to dissolve would explain the differences observed.

SUMMARY

To study the fertilizer value of phosphorus in farm manure, two methods for labeling the inorganic and organic forms of phosphorus in sheep manure with P^{32} were investigated: (a) feeding the sheep $\text{KH}_2\text{P}^*\text{O}_4$ with the forage and (b) incubation of the sheep feces with $\text{KH}_2\text{P}^*\text{O}_4$ as well as with radioactive superphosphate for 22 days.

The phosphorus in the feces was separated into the following fractions: inorganic; phospholipid; acid-soluble organic; and protein-bound; and the degree of labeling was determined in the different fractions. Only 18 per cent of the total phosphorus in the sheep feces was in organic form, most of which appeared in the protein-bound fraction.

It was found that 84 to 90 per cent of the phosphorus in the organic forms in the sheep feces was labeled when the animal was fed the $\text{KH}_2\text{P}^*\text{O}_4$ supplement with the forage. The organic phosphorus labeled varied for the different fractions, ranging from 43 to 94 per cent for samples incubated with $\text{KH}_2\text{P}^*\text{O}_4$ and from 22 to 50 per cent for samples incubated with radioactive superphosphate.

REFERENCES

- (1) FUNATSU, T. 1908 On different forms of phosphoric acid in press cakes. *Tokyo Imp. Univ. Coll. Agr. Bul.* 7: 457-459.
- (2) GHANI, M. O. 1941 Fractionation of phosphoric acid in organic manures. *Indian Jour. Agr. Sci.* 11: 954-958.
- (3) HEVESTY, G. 1948 Radioactive Indicators. Interscience Publishers, Inc., New York.
- (4) KAMEN, M. D. 1947 Radioactive Tracers in Biology. Academic Press, Inc., New York.
- (5) KITSON, R. E., AND MELLON, M. G. 1944 Colorimetric determination of phosphorus as molybdivanadophosphoric acid. *Indus. and Engin. Chem., Analyt. Ed.* 16: 379-388.
- (6) MCAULIFFE, C. Determination of radiophosphorus in plant material by solution counting. *Analyt. Chem.* (In press).
- (7) MCAULIFFE, C., PEECH, M., AND BRADFIELD, R. 1949 The utilisation by plants of phosphorus in farm manure. II. This issue *Soil Sci.*

- (8) Peperzak, P. 1948 Phosphorus Compounds in Manures. Ames, Iowa. (Master's Thesis, Iowa State College.)
- (9) PETERS, J. P., AND VAN SLYKE, D. D. 1932 Quantitative Clinical Methods, vol. 2. Williams and Wilkins Co., Baltimore.
- (10) TSUDA, S. 1909 On the different forms of phosphoric acid in organic manures. *Tokyo Imp. Univ. Col. Agr. Jour.* 1: 167-170.
- (11) UMBREIT, W. W., BURRIS, R. H., AND STAUFFER, J. F. 1945 Manometric Techniques and Related Methods for the Study of Tissue Metabolism. Burgess Publishing Co., Minneapolis.

UTILIZATION BY PLANTS OF PHOSPHORUS IN FARM MANURE:

II. AVAILABILITY TO PLANTS OF ORGANIC AND INORGANIC FORMS OF PHOSPHORUS IN SHEEP MANURE¹

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On many farms more phosphorus is added to the soil in the form of manure than in the form of superphosphate. There is evidence that phosphorus added in manure may react quite differently with the soil, to the growing crop and to chemical soil tests, from phosphorus added as superphosphate. The object of this investigation was to study the relative availability to plants of the organic and inorganic forms of phosphorus in farm manure, and to determine the utilization of the phosphorus in superphosphate when this fertilizer material was applied to the soil alone and in conjunction with farm manure.

It has been difficult, if not impossible, by conventional methods to differentiate in the crop between the fractions of the phosphorus coming from different sources. Radiophosphorus provides a relatively simple method of attacking the problem.

The literature on the relative availability of phosphorus in manure and superphosphate is controversial. Many investigators (1, 4, 11) have reported that manure, despite its low phosphorus content, is an effective source of phosphorus. Guyon (10) found that plants utilized less phosphorus from manure than from common inorganic sources, but Dorph-Peterson (6) reported equal uptake of phosphorus. Gericke (9) in a statistical treatment of data from numerous fertilizer experiments concluded that the phosphorus in manure was inferior to that in inorganic sources. Pierre (19) and Salter and Schollenberger (22) discussed the indirect effects of manure in decreasing the fixation of inorganic phosphorus and in increasing the solubility of inorganic forms of soil phosphorus.

Midgley and Dunklee (16) found that crop yield responses to the application of superphosphate in conjunction with manure were consistently better than those obtained when superphosphate was applied directly to the soil, particularly on high-phosphorus-fixing soils. This was attributed to conversion of the inorganic phosphate into organic compounds that are slowly available to plants, and to decreased fixation of phosphorus in the superphosphate because of less intimate contact with the soil. Das (5) and Copeland and Merkle (4) also reported beneficial effects of adding superphosphate with manure. On the other hand, Salter and Schollenberger (22) questioned the advisability of adding superphosphate to manure because of reversion to tricalcium phosphate.

EXPERIMENTAL PROCEDURE

The experiment was carried out in a greenhouse, with Italian rye grass as the indicator crop. Mardin silt loam, obtained from a limed area on the Mt. Pleasant experimental field near Ithaca, New York, was passed through a $\frac{1}{4}$ -inch mesh

¹ This work was supported in part by the grant from the Industry Phosphate Research Committee.

screen, and dried with thorough mixing. Samples of soil weighing 3,100 gm. were placed in number 10 tin cans, coated inside with a clear Duco enamel. The soil had a pH value of 6.2 and contained 29 pounds P per acre as determined by the modified Truog method (18). As a basal treatment the soil received 200 pounds K as KCl and 100 pounds Mg as 3 $\text{MgCO}_3 \cdot \text{Mg}(\text{OH})_2$ per acre, allowance being made for the K content of manure. Nitrogen was added at the rate of 20 pounds per acre as NH_4NO_3 initially and at required intervals to treatments not receiving manure.

TABLE 1

Organic and total phosphorus content, specific activity, and degree of labeling of organic phosphorus fraction of fertilizer materials used in greenhouse experiment

DESIGNATION AND DESCRIPTION OF FERTILIZER MATERIALS	TOTAL PHOSPHORUS	SPECIFIC ACTIVITY†	ORGANIC P TOTAL P $\times 100$	PROPORTION OF ORGANIC PHOSPHORUS LABELED
	per cent	milli-curie/gm. P	per cent	per cent
Manure* (feces from sheep fed $\text{KH}_2\text{P}^*\text{O}_4$)	1.26	0.65	15.7	89
$\text{KH}_2\text{P}^*\text{O}_4$ aged with manure (sheep feces from same animal fed on same forage containing no radiophosphorus; incubated with $\text{KH}_2\text{P}^*\text{O}_4$ at 37°C. for 22 days)	1.25	0.95	15.1	47
Super* aged with manure (same as above except that labeled superphosphate was substituted for $\text{KH}_2\text{P}^*\text{O}_4$)	2.06	0.65	7.6	28
Manure (sheep feces from the same animal fed on same forage but containing no radiophosphorus)	0.98			
Protein-bound P* (obtained from manure*)	0.17	0.62	100.0	90
Super* (superphosphate containing labeled phosphorus†)	9.0	1.20		
Super (ordinary commercial superphosphate)	6.0			

* Indicates phosphorus in material labeled with P^{32} .

† Specific activity based on total phosphorus content at start of greenhouse experiment.

‡ Kindly supplied by the Division of Soils and Fertilizers, Bureau of Plant Industry, Soils, and Agricultural Engineering, U. S. Department of Agriculture.

In the present studies the phosphorus in the sheep manure was labeled with P^{32} by two procedures as described previously (14). The phosphorus content, the specific activity of the materials, and the proportion of the organic phosphorus labeled are summarized in Table 1. All manure samples were dried rapidly in a forced-circulation oven at 70°C., ground, and thoroughly mixed before application to the soil. The protein-bound phosphorus was prepared by extracting with 5 per cent trichloroacetic acid the feces from the sheep fed $\text{KH}_2\text{P}^*\text{O}_4$. This residue was washed with 0.1 N HCl followed by distilled water to remove the trichloroacetic acid, which is very toxic to plants. Sufficient calcium carbonate was added to neutralize the hydrogen-saturated residue.

The treatments and rates of application of phosphorus are shown in table 2.

All treatments were replicated four times with the exception of treatments 1, 3, and 6, in which there were twelve replicates in the first cutting, eight in the second, and four in the third, four replicates being sacrificed after each cutting to permit chemical studies on the soil. In treatments 6 and 7, superphosphate and manure were thoroughly mixed together before application. In treatment 6 the superphosphate contained P^{32} , whereas in treatment 7 the manure phosphorus was labeled. Inasmuch as these two treatments are otherwise equivalent as to physical structure, aeration, nutrient supply, and other properties, it is possible to determine from treatments 6 and 7 the proportion of phosphorus in the plant

TABLE 2
Yield and phosphorus content of Italian rye grass on Mardin silt loam under different treatments

TREATMENT†	P ADDED TO SOIL	YIELD AT CUTTING			TOTAL P IN PLANT AT CUTTING		
		1	2	3	1	2	3
	lb./A.	gm.	gm.	gm.	per cent	per cent	per cent
1. Soil alone	—	3.27	4.04	2.11	0.280	0.306	0.563
2. Manure*	102	3.43	3.07	2.37	0.370	0.604	0.729
3. Super*	105	4.81	4.31	2.24	0.284	0.453	0.685
4. Manure* (band)	102	4.08	3.22	2.27	0.329	0.538	0.698
5. Super* (band)	105	4.71	4.12	2.34	0.290	0.454	0.633
6. Super* + manure	(105 + 90) 200	3.54	3.88	2.36	0.376	0.544	0.717
7. Super + manure*	(99 + 102) 201	4.06	3.20	2.34	0.392	0.634	0.733
8. Super* + manure (band)	200	3.74	3.02	2.43	0.351	0.610	0.673
9. Super + manure* (band)	201	4.15	3.12	2.37	0.332	0.631	0.692
10. Super* aged with manure	165	3.48	3.11	2.17	0.397	0.681	0.745
11. KH_2PO_4 aged with manure	101	3.13	2.90	2.59	0.372	0.662	0.672
12. Protein-bound P*	48†	1.70	2.36	1.44	0.405	0.482	0.568
L.S.D. 0.05		0.19	0.27	0.12	0.014	0.027	0.041
0.01		0.29	0.42	0.19	0.021	0.042	0.062

† For designation and description of material see table 1.

† One replicate received 36 pounds P per acre.

derived from each of the two sources when superphosphate and manure are applied together as well as that derived from native soil phosphorus.

Where the fertilizer materials were mixed throughout the soil, a small glass churn was used. The band placements were made by removing 1 inch of soil from the pot, layering in the fertilizer material uniformly, and replacing the 1 inch of soil. After the fertilizer was mixed with the soil, 115 Italian rye grass seeds were planted and the soil was brought to a moisture content of 27 per cent and maintained at this level. When the seedlings were 2 to 3 inches high, they were thinned to a total of 95 plants per pot. The planting date was July 20, and cuttings were taken 36, 60, and 91 days after seeding.

Between the first and second cutting it became apparent that the plants in

treatments receiving the manure were not obtaining sufficient nitrogen. To keep nitrogen from being the limiting factor during the remainder of the experiment, 20 pounds N per acre was added every two weeks to all pots starting 10 days before the second cutting.

The harvested grass was dried at 75°C. and ground through a 20-mesh screen. The P^{32} activity was determined by counting from the plant-ash solution (15) to a theoretical standard deviation of less than 0.7 per cent. The activity in the samples was sufficient to give a minimum rate of 1,000 counts per minute at the third cutting. In the analysis of all plant samples, the specific activity was determined to a mean standard deviation of a single measure of 1.9 per cent. Total phosphorus was determined on an aliquot of this ash solution by the molybdivanadophosphoric acid method (12).

RESULTS AND DISCUSSION

The yield data summarized in table 2, with the exception of treatments 1, 6, and 12, show a decrease in yield with successive harvests. In the first cutting, there was an apparent response to phosphorus for all treatments except 11 and 12. The yields of treatment 12 are not comparable with those of the other treatments because of the deleterious effect of the trichloroacetic acid. The lack of nitrogen, which was observed early in the experiment, accounts for the lower yield values where manure was applied. This effect of insufficient nitrogen in the manure treatments was especially evident in the second cutting. Nitrogen was added by mistake to treatment 6 after the first cutting, thus accounting for the high yield of the second cutting. Except for treatments 10 and 12, yields for all phosphorus treatments exceeded that of the control at the third cutting when nitrogen apparently was no longer a limiting factor.²

It is obvious from table 2 that the phosphorus content of the grass increased markedly with successive cuttings. With only one exception in the third cutting, the phosphorus content of the plants in treatments 1, 3, and 5, receiving no phosphorus or only superphosphate, was less than that of any of the other treatments. The phosphorus content of the plants was lower where the manure was added in a band than where it was mixed throughout the soil.

The percentage of phosphorus in the plant material derived from the added fertilizer at each of the three harvests is shown in table 3. More phosphorus was taken up from superphosphate than from manure in all three cuttings when both materials were mixed with the soil. This difference was small at the third cutting, however, and if uptake were plotted against time and the curves extrapolated, they would cross. The relatively slow decrease in availability of phosphorus in manure may be attributed to the protective action of manure in preventing intimate contact of the inorganic phosphorus with the soil, thus lessening fixation (4, 16). Also, although the phosphorus in organic combinations is less available, its availability upon gradual release to the plants should remain relatively more constant, as found with the protein-bound phosphorus fraction.

² All differences discussed in this paper are at least significant at the 0.05 level.

With band placements the applied phosphorus was utilized by plants more efficiently from manure than from superphosphate. The proportion of phosphorus, in plants, derived from the applied phosphorus in the band was initially higher than that of the corresponding treatments where the fertilizers were mixed throughout the soil. But by the end of the second cutting, the proportion derived from superphosphate placed in a band had fallen below that from superphosphate mixed throughout the soil. Likewise, the proportion derived from manure placed in a band was initially much higher than that from manure thoroughly incor-

TABLE 3

Proportion of phosphorus in Italian rye grass derived from applied labeled fertilizer, and percentage recovery of added fertilizer

TREATMENT†	P IN PLANT DERIVED FROM LABELED FERTILIZER AT CUTTING			RECOVERY OF LABELED FERTILIZER			
	1	2	3	Cutting 1	Cutting 2	Cutting 3	Total
	<i>per cent</i>	<i>per cent</i>	<i>per cent</i>	<i>per cent</i>	<i>per cent</i>	<i>per cent</i>	<i>per cent</i>
2. Manure*	37.1	31.2	29.0	2.9	3.6	3.1	9.6
3. Super*	45.6	35.6	30.5	3.7	4.2	2.9	10.7
4. Manure* (band)	58.6	39.0	32.5	4.9	4.3	3.2	12.4
5. Super* (band)	52.2	34.3	26.5	4.3	3.9	2.4	10.5
6. Super* + manure	34.3	26.1	24.3	2.8	3.3	2.5	8.6
7. Super + manure*	27.6	24.5	22.1	2.7	3.1	2.4	8.2
6 + 7	61.9	50.6	46.4	2.8	3.3	2.5	8.7
8. Super* + manure (band)	33.9	23.3	22.0	2.7	2.6	2.2	7.5
9. Super + manure* (band)	33.5	22.2	19.8	3.2	2.7	2.1	8.0
8 + 9	67.4	45.6	41.8	3.0	2.8	2.2	7.9
10. Super* aged with manure	56.1	46.6	43.0	2.9	3.8	2.7	9.3
11. $\text{KH}_2\text{P}\cdot\text{O}_4$ aged with manure	41.2	33.3	30.3	3.0	4.0	3.3	10.4
12. Protein-bound P*	5.1	5.7	6.5	0.5	0.9	0.7	2.0
L.S.D. 0.05	0.6	0.6	0.9				
0.01	1.0	1.0	1.3				

† For designation and description of material see table 1.

porated into the soil, but the two methods of application were almost equally efficient by the third cutting.

The utilization, by plants, of phosphorus from the protein-bound fraction was considerably lower than that from the other sources, but it increased very slowly with time. The mineralization or utilization, by plants, of nucleic acid in soils has been demonstrated by several investigators (2, 8, 17, 21). As shown in table 3, the proportion of phosphorus in plants derived from the applied phosphorus was somewhat higher in treatment 11 ($\text{KH}_2\text{P}\cdot\text{O}_4$ aged with manure) than in treatment 2 (manure*), indicating that incubation of manure has slightly increased the availability of phosphorus.

It is evident from table 3 that phosphorus in superphosphate was more available to plants than that in manure when the two materials were mixed and applied together. When superphosphate and manure were mixed and placed in a band, the same amount of phosphorus was taken up from the two sources in the first cutting, but the relative uptake was slightly greater from superphosphate in the second and third cuttings. Since the pairs of treatments 6 and 7 and 8 and 9 are identical except for the constituents labeled, the percentage of phosphorus derived from the two forms of fertilizer has been combined in table 3. Such a summation shows the beneficial effect of the band placement in the first cutting only. Thorough incorporation of the two materials into the soil resulted in a higher proportion of phosphorus in plants from the two combined sources

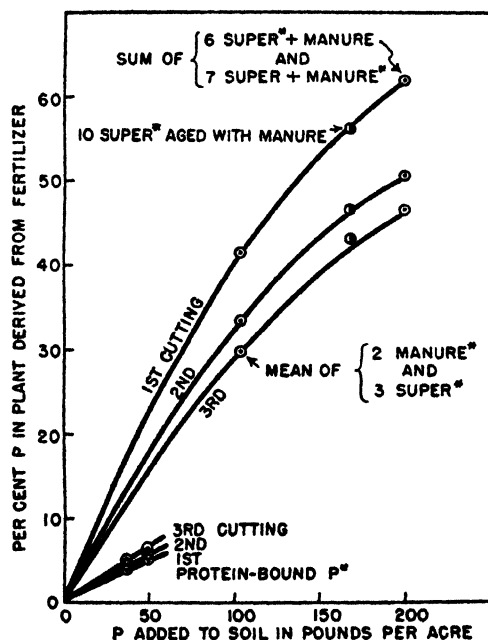


FIG. 1. PERCENTAGE OF PHOSPHORUS DERIVED BY RYE GRASS FROM CERTAIN SELECTED FERTILIZER TREATMENTS APPLIED AT DIFFERENT RATES

in the second and third cuttings. Inasmuch as thorough mixing of superphosphate also resulted in higher utilization of applied phosphorus in the second and third cuttings, it may be concluded that the initial advantage of band placement in minimizing phosphorus fixation was later outweighed by the greater accessibility to roots of the fertilizer mixed throughout the soil.

In figure 1, the percentage of phosphorus in the plant derived from the fertilizer has been plotted against the quantity of phosphorus added to the soil for certain selected treatments to evaluate the effectiveness of superphosphate aged with manure (different rate of phosphorus application) as compared with the other treatments. The curves were drawn using the mean value for percentage of phosphorus in plants derived from the fertilizer for treatments 2 and 3 at

the 100-pound rate, and the summation of values for treatments 6 and 7 at the 200-pound rate. It will be noted that the percentage phosphorus derived from the fertilizer in treatment 10 fell on these curves for the three cuttings, indicating that there was apparently neither a beneficial nor a detrimental effect upon incubating superphosphate with manure for 22 days compared with direct application to the soil or direct application to the soil with manure. Midgley (16) has pointed out that the tricalcium phosphate formed when superphosphate is added to manure may be very different in its availability to plants after drying. In the present investigation, all manures were dried to assure uniform P^{32} distribution by mixing and to facilitate weighing and mixing of the materials with the soil.

TABLE 4

Absorption of phosphorus by rye grass from the soil and from the fertilizer
In pounds per acre

TREATMENT††	SOIL P ABSORBED†				LABELED FERTILIZER P ABSORBED				P ABSORBED, TREATED MINUS UNTREATED‡
	Cut-ting 1	Cut-ting 2	Cut-ting 3	Total	Cut-ting 1	Cut-ting 2	Cut-ting 3	Total	
1. Soil alone	5.9	8.0	7.6	21.4					
2. Manure*	5.1	8.1	7.8	21.0	3.0	3.6	3.2	9.8	9.4
3. Super*	4.7	8.0	6.8	19.4	3.9	4.4	3.0	11.3	9.3
4. Manure* (band)	3.6	6.8	6.8	17.1	5.0	4.3	3.2	12.6	8.3
5. Super* (band)	4.2	7.7	7.0	18.9	4.5	4.1	2.5	11.1	8.5
10. Super* aged with manure ..	5.3	7.1	5.9	18.3	4.4	6.3	4.5	15.6	11.0
11. KH_2PO_4 aged with manure ..	4.3	8.1	7.7	20.1	3.1	4.1	3.4	10.5	9.2
12. Protein-bound P^*	4.2	6.8	4.9	15.9	0.23	0.41	0.32	0.96	-4.5

†† For designation and description of material see table 1.

† Soil P plus fertilizer P is equal to total phosphorus absorption.

‡ Calculated as the difference in total phosphorus absorption, for the three cuttings, between the fertilized and untreated soils.

The three small curves represent the utilization of the protein-bound phosphorus at 36- and 48-pound rates of application. A comparison of these curves with the other curves reveals that the protein-bound phosphorus was utilized approximately 20 per cent as efficiently in the first cutting as was phosphorus from superphosphate or manure taken as a whole, and that in the third cutting the efficiency had increased to almost 30 per cent.

The percentage recovery by plants of the applied fertilizer phosphorus for the three harvests is shown in table 3. With the exception of treatment 12, recoveries for individual cuttings varied from 2 to 5 per cent, and the totals for the three cuttings varied from 7.5 to 12.4 per cent. The percentage of applied phosphorus utilized by plants was fairly constant for any given rate of phosphorus application and decreases with increasing rate of application.

The absorption of phosphorus by the plant from the soil and from the fertilizer is shown in table 4. The phosphorus derived from the soil did not decrease greatly

from that of the untreated soil in many of the treatments, particularly in the second and third cutting. The uptake of fertilizer phosphorus decreased with successive cuttings in the case of band placements, whereas the largest quantity was removed in the second cutting for other treatments. The last two columns compare the absorption of fertilizer phosphorus as revealed by radiophosphorus and by the past practice of calculating the recovery as the difference in total phosphorus uptake between the fertilized and the unfertilized crop. The latter method gives values which are from 5 to 35 per cent low.

The available phosphorus in soil samples taken after the first and second cuttings from treatments 1, 3, and 6 was determined by Dyer's citric acid method (7). A 100-gm. sample of air-dry soil was shaken with 1 liter of 1 per cent citric acid solution for 60 minutes. Total phosphorus was determined by the isobutyl alcohol method developed by Pons and Guthrie (20), and, after concentration of

TABLE 5

Recovery of applied phosphorus by plants and by extraction of soil with 1 per cent citric acid solution

TREATMENT†	CUTTING	P IN SOIL	PROPORTION OF TOTAL PHOSPHORUS DERIVED FROM FERTILIZER	
			Soil extract	Plant
		lb./A.	per cent	per cent
1. Soil alone	1	20.1		
	2	16.0		
3. Super*	1	46.5	36.7	45.6
	2	45.7	36.1	35.6
6. Super* + manure	1	61.2	33.9	34.3
	2	61.5	28.7	26.1

† For designation and description of material see table 1.

the soil extract, the P^{32} activity was determined by solution counting. From the comparisons of the proportion of total phosphorus derived from the fertilizer, shown in table 5, it is evident that recovery of applied phosphorus by the citric acid method agreed remarkably well with that found in plants. The phosphorus extracted by citric acid increased regularly with fertilizer application.

It will be noted from table 3 that the percentage of phosphorus in the plants derived from the labeled fertilizer decreased with time in all treatments except 12. The decrease with time in the band placements may be explained, at least in part, by root extension into soil not receiving the fertilizer, but the same explanation would not account for the somewhat smaller decrease observed even when the fertilizer materials were thoroughly mixed with the soil. Three contributing factors may be suggested in explanation of this phenomenon:

1. *Chemical fixation of phosphorus.* The concentration of phosphorus in soil solution, following an application of phosphatic fertilizer, is primarily determined and replenished

by the fertilizer phosphorus, which is relatively more soluble than the native soil phosphorus. The effective surface of the fertilizer solid phase and consequently the solubility of phosphorus should decrease with time upon continued dissolution and subsequent fixation of the dissolved phosphorus. The concentration of phosphorus in soil solution should then decrease gradually with time as the relative contribution of the native soil phosphorus in replenishing the phosphorus in soil solution becomes more and more significant. In consequence, the specific activity of phosphorus in the soil solution should thus decrease with time, aside from natural decay. Obviously, it is the specific activity of phosphorus in soil solution, regardless of its concentration, that determines the proportion of phosphorus in plants derived from the labeled fertilizer.

2. *Isotopic exchange.* It was tacitly assumed above that the plants absorb phosphorus from different forms that are not in isotopic equilibrium with each other through the medium of soil solution. The isotopic exchange of added P^{32} for the P^{31} of the soil phosphorus in aqueous soil suspensions has been demonstrated by Dean (13), and the work in progress in the authors' laboratory has shown that appreciable isotopic exchange takes place in soils even at the moisture equivalent when the fertilizer is thoroughly mixed with the soil. Prolonged isotopic exchange would thus continue to decrease the specific activity of phosphorus in soil solution without necessarily any net change in the phosphorus available to plants, and this in turn would be reflected in the lower apparent utilization of applied phosphorus by plants.

3. *Microbiological conversion of phosphorus.* Microbiological conversion of phosphorus should produce the same result as isotopic exchange. In general there is a large microbiological population in soils, and the organisms are known to have a high phosphorus content (3). If the organisms are in a steady state, death and mineralization balanced by growth, there will be no net change in the amount of the soil phosphorus available to plants. But the release of phosphorus, P^{31} , from microbial bodies upon death and relatively greater utilization of the applied phosphorus containing P^{32} during the growth of new organisms would lead to lower specific activity of phosphorus in the soil solution with time. That this occurs was demonstrated by the labeling of the organic phosphorus compounds in manure (14). Thus, through biological activity as well as isotopic exchange, the available phosphorus for plant growth may remain unchanged, yet the specific activity of the phosphorus available to the plant will continue to decrease with time.

The relative significance of the last two factors on the specific activity of phosphorus in the plants is not known at present. Until this is determined, some caution should be exercised in interpreting the results of tracer experiments with radiophosphorus, especially when the phosphatic fertilizer is mixed thoroughly with the soil. In the present experiments, the effect of isotopic exchange and microbiological conversion could not have been sufficiently different between treatments to invalidate the comparison of the extent of utilization by plants of the phosphorus from superphosphate with that from organic and inorganic forms present in manure.

SUMMARY

By means of radiophosphorus, the utilization by plants of phosphorus from manure and superphosphate, when these two phosphorus sources were applied separately and together, was determined in a greenhouse experiment using Italian rye grass as the indicator crop.

The phosphorus fertilization had little effect on the yield of the rye grass. The phosphorus content of the plants increased greatly with successive cuttings and, in general, the plants that received manure contained a higher percentage

of phosphorus than those receiving only superphosphate. The phosphorus content of the plants was lower when the fertilizer materials were placed in a band than when they were thoroughly incorporated into the soil.

The percentage of phosphorus in the plants derived from the added fertilizer varied from 28 to 67 in the first cutting, and from 20 to 46 in the third cutting. In all treatments, with the exception of protein-bound phosphorus, the proportion of phosphorus in plants derived from added fertilizer decreased with time. The phosphorus from superphosphate was somewhat more available than that from manure, particularly in the first cutting. With time, there was little difference in availability, however, between the two sources of phosphorus.

Incubating superphosphate with manure for 22 days had neither a beneficial nor a detrimental effect, as compared with direct application to the soil of superphosphate and manure immediately after mixing of the two materials. Incubation of manure for 22 days slightly increased the availability of phosphorus. In the first cutting, utilization by plants of applied phosphorus was higher in treatments involving band placement than in treatments in which the fertilizer material was mixed with the soil. By the end of the second and especially the third cutting, the band placement proved less efficient than the uniform mixing throughout the soil.

The protein-bound phosphorus in manure was only 20 to 30 per cent as efficient as the phosphorus in superphosphate or in manure taken as a whole.

The applied phosphorus recovered by plants in the three cuttings varied, with treatments, from 8 to 12 per cent except for the protein-bound phosphorus, of which only 2 per cent was recovered despite the lower rate of application.

The recovery of applied phosphorus by plants agreed remarkably well with that obtained by extraction of the soil with 1 per cent citric acid solution.

Isotopic exchange and biological conversion of phosphorus may decrease the specific activity of phosphorus in the plants and affect the interpretation of results.

REFERENCES

- (1) BEAR, F. E., KING, W. A., AND BENDER, C. B. 1946 The dairy cow as a conserver of soil fertility. *N. J. Agr. Exp. Sta. Bul.* **730**: 1-11.
- (2) BERTRAMSON, B. R., AND STEPHENSON, R. E. 1942 Comparative efficiency of organic phosphorus and of superphosphate in the nutrition of plants. *Soil Sci.* **63**: 215-227.
- (3) BUCHANAN, R. E., AND FULMER, E. I. 1928 Physiology and Biochemistry of Bacteria. vol. 1. Williams & Wilkins Co., Baltimore.
- (4) COPELAND, O. L., AND MERKLE, F. G. 1942 The influence of certain soil treatments upon the fixation and availability of applied phosphates. *Soil Sci. Soc. Amer. Proc.* (1941) **6**: 321-327.
- (5) DAS, S. 1944 The manurial value of different mineral phosphates in calcareous soils. *Indian Jour. Agr. Sci.* **14**: 268-272.
- (6) DORPH-PETERSON, K. 1946 Forsøg med Stalgødning og Kunstgødning ved Lyngby 1910-1942. *Tidsskr. Planteavl.* **50**: 555-616. [Abstract in *Soil and Fert.* **10**: 175.]
- (7) DYER, B. 1894 On the analytical determination of probably available "mineral" plant food in soils. *Trans. Chem. Soc. Jour.* **65**: 115-167.
- (8) DYER, W. J., AND WRENSHALL, C. L. 1941 Organic phosphorus in soils: III. *Soil Sci.* **51**: 323-329.

- (9) GERICKE, S. 1943 Is the phosphoric acid of manure better utilized? *Forschungsdienst* **16**: 283-291. [Abstract in *Chem. Abs.* **39**: 1954.]
- (10) GUYON, G. 1946 La Valeur des éléments fertilisants du fumier de ferme. *Ann. Agron.* **16**: 103-106.
- (11) HARTLEY, K. T., AND GREENWOOD, M. 1933 The effect of small applications of farm-yard manure on cereals in Nigeria. *Empire Jour. Exp. Agr.* **1**: 113-121.
- (12) KITSON, R. E., AND MELLON, M. G. 1944 Colorimetric determination of phosphorus as molybdivanadophosphoric acid. *Indus. and Engin. Chem., Analyt. Ed.* **16**: 379-383.
- (13) MCAULIFFE, C. D., ET AL. 1948 Exchange reactions between phosphates and soils: Hydroxylic surfaces of soil minerals. *Soil Sci. Soc. Amer. Proc.* (1947) **12**: 119-123.
- (14) MCAULIFFE, C., AND PEECH, M. 1949 The utilization by plants of phosphorus in farm manure: I. This issue *Soil Sci.*
- (15) MCAULIFFE, C. Determination of radiophosphorus in plant material by solution counting. *Analyt. Chem.* (In press.)
- (16) MIDGLEY, A. R., AND DUNKLEE, D. E. 1945 The availability to plants of phosphates applied with cattle manure. *Vt. Agr. Exp. Sta. Bul.* **525**: 1-22.
- (17) PEARSON, R. W., NORMAN, A. G., AND HO, C. 1942 The mineralization of the organic phosphorus of various compounds in soil. *Soil Sci. Soc. Amer. Proc.* (1941) **6**: 168-175.
- (18) PEECH, M., ET AL. 1947 Methods of soil analysis for soil fertility investigations. *U. S. Dept. Agr. Cir.* **757**: 1-25.
- (19) PIERRE, W. H. 1948 The phosphorus cycle and soil fertility. *Jour. Amer. Soc. Agron.* **40**: 1-14.
- (20) PONS, W. A., AND GUTHRIE, J. D. 1946 Determination of inorganic phosphorus in plant materials. *Indus. and Engin. Chem., Analyt. Ed.* **18**: 184-186.
- (21) ROGERS, H. T. 1942 Dephosphorylation of organic phosphorus compounds by soil catalysts. *Soil Sci.* **54**: 439-446.
- (22) SALTER, R. M., AND SCHOLLENBERGER, C. J. 1939 Farm manure. *Ohio Agr. Exp. Sta. Bul.* **605**: 1-69.

UTILIZATION OF PHOSPHORUS FROM GREEN MANURES¹

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Plowing under green manures may affect the phosphorus fertility of soils by releasing plant-stored phosphorus to the soil. The rate of release of the phosphorus of green manures for immediate plant use is not definitely known. The existing opinion, however, is that the phosphorus of plant materials is slowly mineralized when incorporated into the soil and in part may be readily absorbed by plants.

Much of the phosphorus of green manures is organic. The release of inorganic phosphorus from these organic compounds may be enzymatic or may result from decomposition of the plant material by microorganisms. The fate of the inorganic phosphorus of plant materials added to the soil may also be influenced by microbial activity. The extent to which this phosphorus is fixed by the soil flora probably varies more or less directly with the quantity of available energy material present at a given time. Hutchinson (2) and Tam and Magistad (4) reported that the action of the microflora only temporarily ties up the phosphates of plant residues returned to the soil. Chang (1), who worked with alfalfa and wheat at various stages of maturity, also expressed this view.

The presence of both organic and inorganic native phosphorus in various changing states in soils has been a complicating factor in determining the influence of green manures. Although green manuring has visible beneficial effects, the specific nature of these effects, whether direct or indirect or both, still remains a matter of conjecture, and only presumptive evidence of the significance of either is available. Through the use of radiophosphorus it is possible to measure the utilization, by crops, of phosphorus from green manures.

PREPARATION OF LABELED PLANT MATERIALS

In the first experiment, plant materials containing P^{32} were obtained by growing plants in a phosphorus-poor soil, Evesboro sand, to which neutron-irradiated KH_2PO_4 was added. Plants were grown in flats containing 100 pounds of soil. The initial activity of the P^{32} applied per flat was approximately 5 millicuries. Inactive KH_2PO_4 was also applied in an amount sufficient to make the total P_2O_5 application 100 pounds per acre. Pilot wheat and Perkin soybeans were selected as the green manure crops. Seeds of these were heavily sown in the greenhouse and allowed to grow for 8 weeks. The tops were then harvested, immediately dried at $60^\circ C.$, and ground.

For the second experiment, a green manure crop, pilot wheat, was grown by using a subirrigated-sand-culture technique. The first 32 days the plants were grown in metal trays (48 by 24 by 6 inches) containing coarse sand and subirrigated with a balanced nutrient solution. At the end of this period, the nutrient

¹ Report of a study made under the Research and Marketing Act of 1946.

solution was removed and the sand washed by repeated flushing with water. Water containing irradiated KH_2PO_4 , activity 15 millicuries per flat, was then used for irrigation the next 7 days. For the remainder of the growing period a phosphorus-free nutrient solution was used. At the end of the total growing period of 53 days, roots and tops were harvested separately. They were cut into pieces 1 to $1\frac{1}{2}$ inches long and dried at 60°C .

TABLE 1
Composition of plant materials used as green manures

MATERIAL	TOTAL PHOSPHORUS	INORGANIC PHOSPHORUS
	<i>per cent</i>	<i>per cent</i>
<i>Experiment 1</i>		
Soybean tops	0.29	0.16
Wheat tops	0.34	0.16
Soybean tops, extracted	0.15	nil
Wheat tops, extracted	0.11	nil
<i>Experiment 2</i>		
Wheat tops	0.58	0.22
Wheat roots	0.43	0.32
Wheat tops, extracted	0.34	nil

TABLE 2
Soils used in greenhouse experiments

SOIL TYPE	SOIL GROUP	pH	TOTAL PHOSPHORUS	ORGANIC PHOSPHORUS	P SOLUBLE IN 0.002N H_2SO_4
			<i>lb / A</i>	<i>lb / A.</i>	<i>lb./A.</i>
Ashkum clay loam	Brown soil	6.2	2,900	1,500	145
Tama silt loam	Gray-brown podzolic	5.1	2,700	1,300	100
Fayette silt loam	Prairie	6.1	2,800	1,200	250
Evesboro loamy sand	Alluvial	5.5	620	220	35

CHARACTER OF MATERIALS AND SOILS USED IN GREENHOUSE EXPERIMENTS

The total and inorganic phosphorus contents of the materials used as green manures are given in table 1. The extracted plant materials were prepared by shaking material ground to pass a 20-mesh screen for 1 minute with a 0.002 N H_2SO_4 solution containing 3 gm. $(\text{NH}_4)_2\text{SO}_4$ per liter. Then the material was filtered through broadcloth, washed with small portions of the H_2SO_4 solution, and dried at 60°C . Presumably all of the phosphorus remaining in materials treated in this way was in organic compounds.

The soils used in the two greenhouse experiments and data pertaining to their phosphorus status are listed in table 2. With the exception of the Evesboro, these soils were high in organic matter and were well supplied with both total and organic phosphorus.

UTILIZATION, BY PLANTS, OF PHOSPHORUS FROM WHEAT AND SOYBEAN
GREEN MANURES

The initial experiment entailed the uptake of phosphorus by rye grass from wheat and soybean green manures and KH_2PO_4 added to Ashkum clay loam. The treatments, as indicated in table 3, were set up as two replications of three pots each. The pots contained 2 kgm. of air-dry soil. The green manures and KH_2PO_4 were added to the soil in amounts sufficient to contain 69 mgm. of phosphorus. Perennial rye grass was seeded on December 9, 1947. The grass was cut 6, 11, and 15 weeks after planting, and the specific activity was determined by the method of MacKenzie and Dean (3).

TABLE 3

Uptake of phosphorus by rye grass from green manures and KH_2PO_4 added to Ashkum clay loam

TREATMENT*	PHOSPHORUS UPTAKE FROM TREATMENTS AT CUTTING				TOTAL PHOSPHORUS APPLICATION ABSORBED BY THREE CROPS	PHOSPHORUS DERIVED FROM TREATMENTS, IN CROPS AT CUTTING			
	1	2	3	4		1	2	3	4
	mgm / pot	mgm / pot	mgm / pot	mgm / pot	per cent	per cent	per cent	per cent	per cent
KH_2PO_4	4.1	5.3	4.7		20	66.9	59.0	59.2	—
Soybean tops, mixed in soil	1.1	2.1	2.9		9	51.5	42.8	40.2	—
Wheat tops, mixed in soil	1.6	2.1	4.1		11	54.1	40.1	49.7	—
Soybean tops, layered in soil	1.4	3.4	6.6		16	54.6	57.2	66.8	—
Wheat tops, layered in soil	1.8	4.1	6.0		17	48.3	67.7	69.3	—
Soybean tops, extracted mixed in soil	0.8	0.2	3.4	2.3	6	23.6	14.6	35.0	56.0
Wheat tops, extracted mixed in soil	0.5	0.3	2.9	1.8	5	23.9	16.1	34.4	47.4

* Sixty-nine mgm. phosphorus was added to each pot either in plant material or in KH_2PO_4 . This application was equivalent to approximately 160 pounds P_2O_5 per acre.

Since this was the first green manure experiment of its kind involving use of P^{32} , rather heavy applications of green manures (10–12 tons per acre) were made to assure sufficient uptake of phosphorus for determination of P^{31} and P^{32} . This heavy application caused a depression in the growth of the succeeding crop. This effect was much more apparent and prolonged in the extracted plant material treatments where the application of residues was two to three times the above rate. Despite this depression in yield, the percentage phosphorus in the crop derived from the green manure treatments was fairly uniform for the first three cuttings, and except for the extracted material it compared favorably with that derived from the wholly inorganic source. Layering green manures in the soils permitted a greater uptake of phosphorus from the treatments than did mixing.

The uptake of phosphorus from extracted green manure or from the wholly organic phosphorus source was much less than that from the other materials. When the rye grass had fully recovered, however, from the depressing effect of the heavy application of green manure (after the third cutting and at the time of

TABLE 4

Yield and phosphorus uptake of rye grass grown on soils receiving superphosphate and green manures

Sum of three cuttings per pot

TREATMENT	SOIL	DRY WEIGHT OF PLANTS	TOTAL PHOSPHORUS ABSORBED	ABSORBED PHOSPHORUS DERIVED FROM TREATMENT
		gm	mgm.	mgm.
Superphosphate* mixed in soil	Tama	3.49	14.2	3.2
	Fayette	3.74	20.4	2.3
	Evesboro	2.74	5.6	2.5
Superphosphate† mixed in soil (double rate)	Tama	3.70	16.2	5.7
	Fayette	4.02	22.7	4.4
	Evesboro	3.50	9.6	6.2
Wheat tops* mixed in soil	Tama	5.01	15.2	2.3
	Fayette	5.44	22.0	1.7
	Evesboro	2.84	5.0	1.9
Wheat tops† mixed in soil (double rate)	Tama	5.36	15.1	3.7
	Fayette	6.08	25.6	3.3
	Evesboro	4.05	8.0	3.7
Wheat tops† layered in soil	Tama	4.83	15.2	3.5
	Fayette	5.10	21.5	2.5
	Evesboro	4.72	9.6	4.9
Wheat tops, extracted†, mixed in soil	Tama	3.81	10.4	0.8
	Fayette	4.56	20.8	0.9
Wheat roots† mixed in soil	Tama	3.70	11.7	1.4
	Fayette	4.58	22.1	1.4
L.S.D. (0.05)		0.46	1.2	0.34

* Application of 29 mgm. phosphorus per pot.

† Application of 58 mgm. phosphorus per pot.

the fourth cutting) about half of its phosphorus was obtained from the organic source.

Another greenhouse experiment was conducted in which unground plant material was added at rates of 2 and 4 tons per acre (dry-weight basis) to three different soils and the phosphorus uptake was compared to that of superphosphate. These rates of application were approximately equivalent to adding 50

and 100 pounds P_2O_5 per acre. The treatments are indicated in table 4. These treatments were applied and the soils held in a moist condition for 10 days before rye grass was seeded. This delay in seeding was to permit partial decomposition of green manures. Cuttings of the rye grass were made 34, 53, and 72 days after planting. As in the previous experiment, growth was depressed the first few weeks after planting as a result of the addition of plant materials. This depression, however, was overcome sooner in this experiment than in the first. At the time of the second cutting adverse influence of the green manure was entirely absent; in fact, the soils treated with green manure out-yielded those treated with superphosphate.

Table 4 gives the dry weights, the total phosphorus absorbed, and the phosphorus absorbed from that added as treatments. These values are averages of three replications and the sum of the three cuttings. To simplify this presentation, the data for the individual cuttings are omitted. The highest yields in dry matter were obtained with the Fayette soil and the lowest with the Evesboro. Similar differences occurred in the amounts of total phosphorus absorbed. However, there is as much as a fourfold difference in the amounts of phosphorus absorbed from Fayette and Evesboro soils and less than a twofold difference in the dry weights. Differences in the amounts of treatment phosphorus absorbed by the rye grass growing on the three soils were small.

A comparison of equal quantities of phosphorus in the form of superphosphate and wheat tops mixed throughout the soil indicates that the green manure phosphorus is about 70 per cent as efficient as the superphosphate. Placing the green manure in a layer rather than mixing throughout the soil increased the amount of green manure phosphorus that was absorbed by the rye grass. The phosphorus in the wheat roots does not appear to be so readily available as that of the tops.

DISCUSSION OF RESULTS

The data obtained in this investigation clearly indicate that phosphorus turned under in green manure is available for plant use. The finding that the plants growing on Evesboro loamy sand, a phosphorus-poor soil, could gain as much as half of their phosphorus from the green manure applied at about the usual farm rate particularly indicates that the phosphorus of green manure is available for plant use. The plant absorption of phosphorus varies according to the phosphorus-supplying power of the soil. The phosphorus content of the plant materials growing on Fayette silt loam was the highest, that on Tama silt loam intermediate, and that on Evesboro loamy sand the lowest. The percentage phosphorus derived from the green manure and superphosphate decreased in the reverse order, respectively.

Layering of green manures appears to have a decidedly favorable influence on the uptake of phosphorus. The purpose of layering the green manure was to simulate as nearly as possible conditions in the field when green manures are plowed under. It is unlikely that green manures are so well distributed in field practice as was the materials of the mixed-in soil treatments reported here.

The apparent low utilization of the organic phosphorus as shown by the percentage uptake of the phosphorus of the extracted material needs further investigation. Due consideration must be given to the fact that, to bring all treatments up to a basis of equivalent phosphorus, about twice as much material was added in the form of extracted wheat tops. The presence of this additional amount of plant material partly devoid of its original inorganic phosphorus and soluble nitrogen undoubtedly had some influence in retarding the rate of mineralization of the organic phosphorus.

The results of these greenhouse experiments may not be wholly representative of like experiments in the field. Under field conditions soil temperatures and moisture are quite different.

SUMMARY

Greenhouse experiments on the absorption by rye grass of phosphorus from green manures incorporated in soils gave the following results:

Green manures supplied about 70 per cent as much phosphorus to the succeeding crops as did superphosphate applied on a basis of equivalent phosphorus.

A greater amount of phosphorus was absorbed from green manures when placed in a layer than when mixed with the soil.

More phosphorus was absorbed from natural wheat tops than from wheat tops that were extracted to remove the inorganic phosphorus.

REFERENCES

- (1) CHANG, S. D. 1939 Phosphorus transformations during decomposition of plant materials. *Soil Sci.* **48**: 85-99.
- (2) HUTCHINSON, C. M. 1923 The value of fermented green manures as tested at Pusa by the prevailed plot method. *Agr. Jour. India* **18**: 219-247.
- (3) MACKENZIE, A. J., AND DEAN, L. A. 1948 Procedure for measurement of P^{31} and P^{32} in plant material. *Analyt. Chem.* **20**: 559-560.
- (4) TAM, R. K., AND MAGISTAD, O. C. 1936 Chemical changes during decomposition of pineapple trash under field conditions. *Soil Sci.* **41**: 315-327.

ORGANIC MATTER AND NITROGEN CONTENTS OF SOILS AS INFLUENCED BY MANAGEMENT¹

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The decrease in organic matter in the soils of this country is one of the major agricultural problems of today. Native humus is still too often regarded more as a source of nitrogen for growing crops than as a necessary soil conditioner. Many recommended practices are based on maintaining as much organic matter as possible under the system used, but in most cases these systems have fallen far short of their goal. Calculations of the nitrogen removed in crops compared to nitrogen added by legumes and fertilizers or manures indicate that most programs may be on a negative-nitrogen balance. The extra nitrogen needed to compensate for the negative balance must come from the native humus. Since the native humus contains about 5 to 6 per cent nitrogen, it follows that for each 5 to 6 pounds of nitrogen supplied by the humus, about 100 pounds of soil organic matter must be destroyed. There is, therefore, good reason why the best agricultural soils of this country are going "downhill" literally as well as figuratively, because humus helps produce good tilth, and soils of good tilth erode less readily.

The purpose of this paper is to show and interpret the changes in organic matter and nitrogen that have occurred on corn-belt soils farmed under different rotation and treatment systems, principally during the 10-year interval from 1935 to 1945.

MATERIALS AND METHODS

Soil samples

Surface soils (6½ inches) from nine Illinois experiment fields were analyzed for total carbon and nitrogen. Loess was the dominant parent material. The soils of the Aledo, Hartsburg, Kewanee, Mount Morris, and Joliet fields represented the productive, dark-colored, prairie soils of northern Illinois. The soils of the Ewing, Oblong, Toledo, and Raleigh fields represented the leached and (without treatment) unproductive, light-colored prairie soils of southern Illinois. The samples used were composites of 20 borings per plot taken at the times indicated in the tables.

Detailed data on yields and descriptions of the management systems are given elsewhere². The soil type and rotation and other pertinent data are given in table 1.

¹ Contribution from the department of agronomy, Illinois Agricultural Experiment Station, Urbana, Illinois, based on the master's thesis of Ching-kwei Lee. Published with the approval of the director.

² Bauer, F. C. 1930 Response of Illinois soil to system of soil treatment. *Ill. Agr. Exp. Sta. Bull.* 362: 435-514. 1930. Unpublished data 1946.

Analytical methods

Nitrogen was determined by the Kjeldahl method³. Tiurin's modification of Shollenberger's dichromate procedure was used for the volumetric estimation of carbon⁴.

Detailed analytical results are given in tables 2, 3, and 4. Calculations of the nitrogen removed in the crops were based on the individual yields on each plot,

TABLE 1

Description of light- and dark-colored soils from Illinois experimental fields

EXPERIMENTAL FIELD AND PRINCIPAL SOIL TYPE	CROP ROTATION SYSTEM	DATE START OF FIELD	BASE EX- CHANGE CAPAC- ITY	pH OF UN- TREATED PLOT	REPLACEABLE POTASSIUM OF UN- TREATED PLOT	AVAILABLE PHOSPHORUS OF UNTREATED PLOT
			<i>me./100 gm.</i>		<i>lb /A.</i>	<i>lb /A.</i>
Light-colored soils (strongly leached)						
Ewing, Cisne silt loam	Corn-oats-mixed hay-wheat	1910	11	4.70	37 (low -)	16 (low -)
Toledo, Cisne silt loam	Corn-oats-mixed hay-wheat	1913	11	4.90	45 (low -)	38 (slight)
Raleigh, Hoyle- ton silt loam	Corn-oats-mixed hay-wheat	1910	8-12	4.85	65 (low)	22 (low)
Oblong, Rinard silt loam	Corn-soybeans- wheat-timothy	1912	8-12	5.20	55 (low)	31 (slight)
Dark-colored soils (not strongly leached)						
Mt. Morris, Tama silt loam	Corn-corn-oats- wheat	1910		5.40	185 (high)	47 (medium)
Joliet, Swygert silt loam	Corn-soybeans- corn-oats-wheat -clover-alfalfa hay	1914	27	5.65	190 (high)	20 (low -)
Aledo, Sable silt clay	Corn-corn-oats- wheat	1910	25-35	5.75	275 (high +)	45 (medium)
Hartsburg, Sable silt clay	Corn-corn-oats- wheat	1912	37	6.75	215 (high +)	77 (high)
Kewanee, Musca- tine silt loam	Corn-corn-oats- wheat	1915	20-30	5.70	225 (high +)	35 (slight)

average values being used for crop composition. The estimated organic matter returned as crop residues was based on the grain yields, the respective grain-straw or grain-stover ratios found to hold for the more productive and the less productive soils being used. Each value given is the average of two plots on each

³ Methods of Analysis of the Association of Official Agricultural Chemists, ed. 5, p. 4. Washington, D. C. 1940.

⁴ Tiurin, I. V. Comparative study of methods of determining organic matter in soils. *Acad. Sci. U.S.S.R. Dokuchaev. Inst.* 3: 129-177. 1937.

field from the 100 and 300 series, the same plots being sampled at the different dates.

RESULTS

The results of the study are presented in tables 2 to 7, inclusive. Tables 2 and 3 give the carbon and nitrogen contents of the soils in 1935 and 1945 and the nitrogen removed by crops in the 10-year interval. Table 4 gives the nitrogen and carbon in earlier years where samples were available and the loss of nitrogen up to 1945. Table 5 shows the average C/N ratios and their change with time and treatment. Tables 6 and 7 show the losses and gains for treatments and a calculated nitrogen balance sheet.

The discussion of the results can be divided into several parts: (a) change in nature of soil organic matter; (b) relative change in amount of soil organic matter and nitrogen with different treatments; (c) absolute change in amounts of soil organic matter with time, including the nitrogen balance.

Effect of time and treatment on nature of soil organic matter

Tables 2, 3, and 4 show that large differences in amounts of soil organic matter have been created by time and treatment. The fully treated plots are much higher in organic matter than the check plots. If the original organic matter at the start of the experiment decomposed at a somewhat similar rate on all plots, then the extra organic matter on the treated plots compared to that on the check would be newly formed soil organic matter and, a difference in nature between it and the original humus might be expected. Such a difference might be reflected in the C/N ratio, which is often used as an indication of differences in the gross nature of organic matter. The averaged results in table 5, however, show that this clue to the reason for the larger amounts of soil organic matter in the treated plots is not provided, as the C/N ratios for any one field are closely similar for all treatments and for time. On the light-colored soils the C/N ratios are lower, illustrating the well-known narrowing of this ratio with the aging of soils. In these soils more change might be expected because of this original lower ratio. But, although some slight indication of a higher ratio in the incomplete treatments is obtained, none of the differences are significant.

Relative changes in amount of soil nitrogen with treatment

The changes in the amount of soil nitrogen with time and treatment can be analyzed from two viewpoints, namely, the change for any given treatments with time relative to the check plot and the change in each plot over a given time.

The change with treatment over a given time relative to the check plot is the difference between the check, or no-treatment plot, and the treated plot, at the end of a given interval. Thus, because the average period for the fields as a whole is 34 years, the samples taken in 1945 will reveal differences which have been created during the whole 34 years. The data in table 6 for the 1935 samples give the relative differences after 24 years of treatment: data in table 4 are differences for shorter periods. Only the 1945 and 1935 data are used in table 6. The differ-

ence between the two periods measures the change over the last 10 years of the experiment.

As will be brought out later, these changes, though positive gains relative to the check, are not absolute gains. Absolute gain or loss as used here is measured by the difference between the values obtained on the same plot at two different

TABLE 2

Carbon and nitrogen contents of the dark-colored soils in 1935 and 1945 and calculated nitrogen removal by crops

EXPERIMENT FIELD	TREATMENT*	1935			1945			N REMOVED BY CROPS, 1936-1945
		C	N	C/N	C	N	C/N	
		%	%		%	%		lb./A
Mt. Morris	O	1.77	.170	10.4	1.60	.155	10.3	458
	RL	1.81	.172	10.5	1.71	.159	10.8	493
	RLP	1.83	.181	10.2	1.75	.172	10.2	535
	RLPK	2.01	.192	10.5	1.90	.190	10.0	552
Joliet	O	2.48	.227	10.9	2.31	.213	10.9	628
	RL	2.55	.234	10.9	2.47	.225	11.0	412
	RLP	2.64	.237	11.1	2.56	.235	10.9	424
	RLPK	3.09	.270	11.4	3.03	.283	10.7	487
Aledo	O	2.68	.213	12.5	2.56	.202	12.5	665
	RL	2.87	.228	12.5	2.74	.224	12.3	547
	RLP	2.85	.225	12.6	2.75	.220	12.5	552
	RLPK	2.89	.221	12.7	2.74	.215	12.7	559
Hartsburg	O	2.87	.243	11.8	2.73	.224	12.2	603
	RL	2.84	.244	11.7	2.71	.229	11.9	461
	RLP	2.99	.258	11.6	2.76	.243	11.4	477
	RLPK	3.08	.269	11.5	2.94	.258	11.4	530
Kewanee	O	3.01	.244	12.4	2.85	.226	12.6	662
	RL	3.18	.259	12.3	3.02	.240	12.6	526
	RLP	3.10	.249	12.5	3.00	.235	12.7	520
	RLPK	3.23	.264	12.3	3.42	.264	13.0	537

* O = No treatment; all stover and straws removed with crop; no sweet clover catch crop seeded.

R = All stover and straws returned and plowed under; sweet clover catch crop seeded in small grain.

L = Limestone added to correct acidity.

P = Rock phosphate at varying rates per acre with a total of 4 tons by 1924; residual since 1924.

K = Use of 400 pounds of KCl (0-0-50) in a 4-year rotation (kainite previous to 1929).

time intervals. Relative gain or loss is the difference between two different plots at the same sampling time.

Table 6 shows, for example, that *relative* to the untreated soil, treatment on the RLPK plots on the dark-colored soils has resulted in an average gain of 600 pounds of nitrogen over a 34-year period. This gain was 380 pounds for the 24-year period and the gain in the last 10 years was 220 pounds, or 37 per cent of the total change. Since 10 years is 29 per cent of the total period, a greater pro-

TABLE 3

Carbon and nitrogen contents of the light-colored soils in 1935 and 1945 and calculated nitrogen removed by crops

EXPERIMENT FIELD	TREATMENT*	1935			1945			N REMOVED BY CROPS, 1935-1945
		C	N	C/N	C	N	C/N	
		%	%		%	%		lb./A
Ewing	O	0.99	.099	10.0	0.84	.090	9.3	103
	RL	0.93	.102	9.1	0.95	.093	10.2	229
	RLP	0.94	.104	9.1	0.89	.095	9.4	340
	RLPK	1.23	.130	9.5	1.11	.123	9.1	578
Toledo	O	1.01	.111	9.2	0.97	.096	10.0	150
	RL	1.12	.111	10.1	1.04	.107	9.7	320
	RLP	1.12	.109	10.2	1.06	.100	10.6	322
	RLPK	1.19	.118	10.0	1.16	.114	10.2	531
Raleigh	O	1.10	.125	8.8	1.08	.115	9.4	223
	RL	1.24	.131	9.5	1.28	.129	9.9	226
	RLP	1.28	.135	9.5	1.25	.126	9.9	332
Oblong	O	1.22	.127	9.6	1.17	.115	10.1	316
	RL	1.35	.135	10.0	1.24	.124	10.0	352
	RLP	1.33	.137	9.7	1.24	.128	9.7	502

See footnote table 2.

TABLE 4

Soil nitrogen and carbon contents of fields in earlier years

EXPERIMENT FIELD	TREATMENT*	YEAR	C	N	C/N	DECREASE IN N UP TO 1945	
						Number of years	Decrease
			%	%			%
Joilet	O	1927	2.67	0.253	10.5	18	15.8
	RLP	1930	3.09	0.280	11.0	15	19.7
Hartsburg	O	1926	3.00	0.265	11.3	19	15.3
Kewanee	O	1927	3.03	0.250	12.1	18	9.6
	RL	1930	3.31	0.256	12.9	15	6.3
Ewing	O	1918	1.08	0.111	9.8	27	19.0
	RL	1918	1.18	0.114	10.3	27	18.4
	RLP	1918	1.15	0.124	9.3	27	23.4
	RLPK	1918	1.37	0.130	10.5	27	5.4
Toledo	RL	1926	1.23	0.122	10.1	19	12.3
	RLP	1926	1.17	0.118	9.9	19	15.3
	RLPK	1926	1.13	0.122	9.2	19	6.5
Raleigh	O	1918	1.12	0.132	8.5	27	12.9
	RL	1918	1.35	0.137	9.8	27	5.9
	RLP	1918	1.35	0.139	9.7	27	9.4
Oblong	O	1931	1.36	0.138	9.8	14	16.7
	RL	1931	1.41	0.144	9.8	14	13.9
	RLP	1931	1.45	0.151	9.6	14	13.9

* See footnote table 2.

TABLE 5

Changes in C/N ratio of light- and dark-colored soils with time and treatment

NUMBER OF FIELDS	TREATMENT*	C/N		
		1935	1945	1945 — 1935
<i>Light-colored soils</i>				
4	O	9.4	9.7	0.3
4	RL	9.7	9.9	0.2
4	RLP	9.6	9.9	0.3
2	RLPK	9.7	9.6	—0.1
<i>Dark-colored soils</i>				
5	O	11.6	11.7	0.1
5	RL	11.6	11.7	0.1
5	RLP	11.6	11.5	—0.1
5	RLPK	11.7	11.6	—0.1

* See footnote table 2.

TABLE 6

*Differences in nitrogen for treatment relative to no-treatment**

NUMBER OF FIELDS AVERAGE†	TREATMENT‡	TOTAL SOIL NITROGEN, 1935	DIFFERENCE FOR TREATMENT AFTER 24 YEARS	TOTAL SOIL NITROGEN IN 1945	DIFFERENCE FOR TREATMENT AFTER 34 YEARS	DIFFERENCE FOR 10 YEARS OF TREATMENT	PER CENT§
<i>Light-colored soils</i>							
2	O	2100	—	1860	—	—	—
2	RL	2130	30	2000	140	110	78
2	RLP	2130	30	1950	90	60	67
2	RLPK	2480	380	2370	510	130	25
<i>Dark-colored soils</i>							
4	O	4350	—	4035	—	—	—
4	RL	4515	165	4260	225	60	27
4	RLP	4565	215	4350	315	100	32
4	RLPK	4730	380	4635	600	220	37

* Differences for treatment are positive only in relation to the check plot. See table 7 for absolute losses with time.

† The Toledo and Ewing fields represent the light-colored soils and the Mt. Morris, Aledo, Hartsburg, and Kewanee fields represent the dark-colored soils. These selections are based on completeness of data and similarity of management.

‡ See footnote table 2.

§ Of 34-year difference.

portionate part of the whole relative change occurred in the last 10 years. This coincides with the period of highest yields on the RLPK plots. On the other hand, the RLPK plot on the light-colored soils produced a change of 130 pounds

in 10 years. This was only 25 per cent of the total change, even though higher yields have also been obtained on these plots in the last 10 years. Variation in rate of change on the check plots can also have a marked effect on the relative differences between check plots and other plots at the end of different periods. All of the values indicate that the treatments have had a marked effect on the nitrogen content over the 34-year period except for the RL and RLP treatments on the light-colored soils, which are deficient in potassium and grow very poor crops unless potassium is added.

TABLE 7
Calculated nitrogen balance sheet for field soils between 1935 and 1945

NUMBER OF FIELDS AVERAGED	TREATMENT*	SOIL NITROGEN DECREASE†	ESTIMATED N REMOVED IN CROPS‡	N FROM SOURCES OTHER THAN SURFACE SOIL ORGANIC MATTER§	GAIN IN N FOR TREATMENT RELATIVE TO CHECK||	SOIL N LOSS, PERCENTAGE OF CROP REMOVAL¶	ESTIMATED LOSS OF SOIL N IN 34 YEARS¶¶	ESTIMATED N IN SOIL 34 YEARS AGO
<i>Light-colored soils</i>								
2	O	240	126**	(-114)††	—	190	860	2676
2	RL	130	275	145	259	47	442	2442
2	RLP	180	331	151	265	54	612	2562
2	RLPK	110	554	444	558	20	374	2744
<i>Dark-colored soils</i>								
4	O	315	597**	282	—	53	1070	5105
4	RL	252	507	255	-27	48	860	5120
4	RLP	205	521	316	34	39	697	5047
4	RLPK	95	549	454	172	18	323	4958

* See footnote table 2.

† Based on surface 6½ inches (2,000,000 pounds).

‡ Based on average composition values and grain-straw ratios.

§ Nitrogen in crops minus soil loss.

|| Represents the N balance after subtraction of the check plot balance, that is, the nitrogen economy of the soil-crop system of treated plots relative to the untreated check.

¶ Based on assumption of same rate of loss over whole period.

** Includes straw and stover, which is removed only from the check plots.

†† Nitrogen lost in excess of crop removal.

Absolute changes in amount of soil nitrogen with time

The nitrogen balance sheet in table 7 shows that, although treated plots are higher in nitrogen than untreated plots, as discussed above, the overall trend is a loss of nitrogen on all treatments and checks.

Because no soil samples were taken at the time the fields were started, no accurate values for the absolute change over the whole 34-year period are possible. The 10-year interval between 1935 and 1945 shows nitrogen declining, however, even on the fully treated soils (table 7). With one exception, however, this loss has been less than the amount of nitrogen calculated to have been removed by

the crops during this period. The check plots of the infertile, light-colored soils apparently produce such small crops that these do not use all the nitrogen released from the humus and some is leached away. This is indicated by a negative value of 114 pounds. On the limed plots, where legumes are grown, the values for nitrogen from sources other than surface soil organic matter are perhaps higher than one might expect, since they are based on the approximate calculations of the probable contribution made by legume fixation (table 3). If legume fixation is credited for the extra nitrogen removed from the RLPK plot in addition to surface soil losses, it would require a fixation of about 90 pounds of nitrogen per acre for each legume crop grown. According to lysimeter studies, as high as 12 pounds of nitrogen per year may also be lost by drainage. Although the legumes probably contributed the greatest part of the extra nitrogen, the possibility of nitrogen's coming from sources other than legumes is not ruled out. The light-colored treated soils show a much higher balance in nitrogen relative to the infertile check than do the dark-colored soils. On the dark-colored soils the nitrogen balance is in favor of the check plot when check and the RL treatment are compared. Since estimated values of crop removal are used, the -27 pounds difference is not significant. On the other hand, table 6 shows only a 225-pound gain in nitrogen in favor of the RL plot for 34 years of treatment, or less than 7 pounds a year. The RLP treatment also shows a low nitrogen balance (table 7) even though the relative gains for the whole period are similar to those on the RLPK treatment on the light-colored soils (table 6). From the soil nitrogen loss, as percentage of the nitrogen in crop removal (table 7) it is evident that the decrease in soil nitrogen could account for 18 to 100 per cent of that removed in the crops.

Assuming that the rate of loss over the 10-year period is similar to that for the whole 34-year period, calculations of the total nitrogen lost in 34 years and the computed composition of the soil 34 years ago are presented in table 7. The dark-colored soils give closer agreement between estimates of the original nitrogen content on different plots than do the light-colored soils.

Two sets of values in tables 6 and 7 should be discussed further.

The first set of values, in table 6, shows that, on the dark-colored soils, the difference in nitrogen for treatment over the check after 34 years is 315 pounds on the RLP plot and 600 pounds on the RLPK plot. The RLPK plots give little additional increase in yield from the use of potassium and are not considered potash-deficient; yet they conserve almost twice as much nitrogen in organic forms as do the RLP plots. This raises the question as to whether the muriate of potash affected the biological activity of the soil in such a way as to favor soil organic matter formation by conserving more nitrogen, or by causing further fixation of nitrogen by nonsymbiotic organisms, or perhaps by increasing growth of the sweet clover catch crop, for which yields are not recorded.

The second set of values, in table 7, is for the dark-colored soils, which show a higher nitrogen balance from sources other than soil organic matter on the check plots (282 pounds) than on the RL treated plots (255 pounds). It should be pointed out that average values were used for calculating the nitrogen content

of the crops removed. Normally, crops growing under nitrogen-deficient conditions are relatively lower in nitrogen. This may partly account for the relatively large check plot values in the fourth and fifth columns and the small relative gain for the other plots in the sixth column. Analyses of crops from these fields do not show enough differences in composition between the treated and the untreated plots, however, to account for the relatively large nitrogen removal calculated for the check plots. This use of an average value for nitrogen in these calculations does not entirely account for the high value of 282 pounds for the check plot in table 7. Thus, some source of nitrogen supply other than that from the surface soil organic matter is indicated, and one might speculate that non-symbiotic fixation of nitrogen or utilization of nitrogen from the subsoil has significantly influenced the results.

THE NITROGEN-ORGANIC-MATTER PROBLEM

The soils studied produced immense amounts of crop organic matter between 1935 and 1945. It is calculated, for example, that the dry matter returned in above-ground residues to the Ewing field (a light-colored soil) has been 18,000, 23,000, and 39,000 pounds an acre on the RL, RLP, and RLPK plots, respectively. On the Aledo field (a dark-colored soil) these amounts were 51,000, 51,000, and 52,000 pounds for the same treatments for this period. All straw and stover were removed from the check plots.

There is probably no organic matter production problem, as such, in soils receiving such large amounts of crop residues. The real problem is to use the crop residues wisely and convert them to soil organic matter. A corn crop produces more residue in stover than does a legume crop where one cutting of clover is removed, as in these studies, although the legume residues contain more nitrogen. Straw plowed under may reduce yields, but straw burned in the fields wastes nitrogen. The problem of utilizing crop residues wisely is far from solved. An effective way of utilizing crop residues appears to be leaving them as a mulch on the surface, but a straw mulch, if mineral nitrogen is not added, may reduce yields.

In short, the whole problem of the utilization of crop residues and their conversion to organic matter in the soil appears to be keyed to nitrogen in particular and to soil fertility in general. Soil organic matter cannot be maintained if more nitrogen is removed in crops than is supplied by all sources of nitrogen renewal other than soil organic matter. During each rotation, under the programs studied, large amounts of crop organic matter are grown and returned; the effects apparently do not go over into the next rotation so far as soil maintenance of organic matter is concerned. The crop organic matter plowed under is rapidly oxidized to carbon dioxide and water.

But the fact that the treated plots, growing legumes, are higher in soil organic matter and nitrogen than the check plots is fairly good evidence that some renewal of the soil organic matter is taking place. It is highly improbable that the difference merely indicates a lower rate of decomposition of the original soil organic matter on the treated plots. This interpretation of the data does not support

the pessimistic viewpoint that soil organic matter cannot be renewed, maintained, or increased, but rather supports the viewpoint that the system has not been tried with sufficient nitrogen to balance all that removed through drainage-water losses and cropping.

The average loss of nitrogen from the RLP plots on the dark-colored fields was 205 pounds in 10 years (table 7). One can only speculate as to how much excess nitrogen would have had to be added for maintenance of the soil organic matter. Even with 100 per cent efficiency, it would require 205 pounds or 20.5 pounds per year just to maintain the soil organic matter under similar conditions.

Without extra nitrogen in the rotations studied, there appears to be no hope of maintaining or increasing soil organic matter. When sufficient is learned about mineral nitrogen use and planting rates for average seasonal condition, addition of extra mineral nitrogen to the corn crop may provide the additional nitrogen needed for maintenance and at the same time pay its cost through increased corn yields. How far one can go in selling off crop residues (straw and stover) and still maintain or build up soil organic matter and maintain yields is not known, although the answer appears to depend on use of fertilizer nitrogen and maintenance of all the other nutrients, especially phosphorus and sulfur, removed in the residues. This study indicates that, because of insufficient nitrogen in the system, the immense amounts of organic matter returned are having no more than a short-time effect.

SUMMARY AND CONCLUSIONS

A study of the changes in nitrogen and organic matter in experimental plot soils, under known management at the beginning and end of 10 years and some longer intervals, leads to the following conclusions:

Relatively constant C/N ratios indicate that the nature of the soil organic matter may not have changed significantly with treatment or length of cropping, although rather large differences in amount have been produced during 34 years.

Relative to the untreated (O) plot, the treatments have generally increased the nitrogen and organic matter content of the soil, their influence, in general, being proportional to the deficiency in the soil of the nutrients supplied by the treatments.

Changes with time on the same plots show losses of organic matter and nitrogen, except for one increase between 1935 and 1945 on a Joliet RLPK plot.

The favorable influence of muriate of potash on organic matter and nitrogen maintenance appears to be unusually large on the RLPK plot relative to the RLP plot in view of the low crop response to potassium on these fields.

Fixation of atmospheric nitrogen on the check plots, where no legumes are grown and all crop residues are removed, or utilization of nitrogen from the subsoil is indicated by the nitrogen balance values for the dark-colored soils.

Differences in organic matter between the checks and the treated plots indicate that organic matter could be maintained or built up, provided sufficient nitrogen and other soil nutrients were present. The inability of the soils studied to maintain or increase their organic matter content is, therefore, ascribed primarily to addition of insufficient nitrogen, to these otherwise fertile soils, to balance crop removal and leaching losses.

CYCLIC AND SEASONAL MOISTURE VARIATIONS ON FOUAD I UNIVERSITY FARM, GIZA DISTRICT, EGYPT

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Shortage of irrigation water, reserved for summer requirements, is the chief factor restricting expansion of lowland reclamation in the northern part of the Nile Delta. A total of 26 billion cu.m. of water would meet all the requirements of the country from February to July, when the river is low. During December and January the lands require very little if any irrigation. From August to November the flood water of the river is much more than is needed. If the available 23 billion cu.m. of water which is reserved in Asswan and Gabal-el-awlia reservoirs or discharged by the natural river during February to July were used more economically, it would serve a wider area than the present 4.5 million feddans¹.

The methods of irrigation and the amounts of water applied to the land are conventional, and differ according to season, harvest, and soil texture. The average irrigation-water requirements for Middle Egypt (Lat. 27° to 30° N) are given in table 1. From April to July, only about one third of the land is cultivated; it is occupied by cotton and needs irrigation. Instead of equal distribution of water over the whole area served, the major part is applied to the cotton area, thus doubling the usual requirements.

Meanwhile, and since the installation of the perennial irrigation system, the water table has risen markedly in the Delta and a considerable part of Middle Egypt. This elevation of the water table in most of the aforementioned area is due chiefly to poor drainage and excess irrigation water; in some places it is due to persistent high levels in front of main dams built on the Nile or on main canals (1).

No previous studies have been made to discover whether the amount of irrigation water now being supplied is correct or whether it is in excess of plant needs.

With this in view, the amounts of irrigation water and the moisture content of a loam alluvial soil at different depths were estimated and recorded for a year in the field, to determine the gains and losses in soil moisture.

DESCRIPTION OF SITE AND SOIL PROPERTIES

The farm of the Faculty of Agriculture, Fouad I University, is situated at 30° 2' N and 31° 13' E, in Giza District, about 0.8 km. west to the River Nile. Because of the variability of the soils of alluvial formation, no sequence of layers for the whole area can be described, but the two plots in which this work was carried out are fairly similarly formed. The surface layer is light loam to a depth of about 20 to 30 cm.; the subsurface is a comparatively sticky layer about 15 cm. deep; and the rest of the profile to a depth 130 cm. is made up of sandy

¹ A *feddan* is local unit equal to 4,200.6 square meters.

TABLE 1
Water requirements for Middle Egypt (7)

MONTH*	WATER PER FEDDAN	DEPTH	MONTH	WATER PER FEDDAN	DEPTH	MONTH	WATER PER FEDDAN	DEPTH
	CM.M.	CM.		CM.M.	CM.		CM.M.	CM.
Jan.	242.8	5.8	May	545.7	13.0	Sept.	1032.0	24.6
Feb.	641.6	15.3	June	610.0	14.5	Oct.	1027.9	24.5
March	584.5	13.9	July	829.4	19.7	Nov.	670.0	16.0
April	526.0	12.5	Aug.	1043.9	24.9	Dec.	300.0	7.2

* The figures for February to July are calculated from the actual discharge, for 1934 to 1937, of Ibrahimiah Canal, which serves this area. (Use of data by permission of the Hydrological Section, Ministry of Public Works, Egypt.)

TABLE 2
Mechanical analyses of the profile of plots I and II*

DEPTH	COARSE SAND 2.0-0.2 MM.	FINE SAND 0.2-0.02 MM.	SILT 0.02-0.002 MM.	CLAY + LOSS ON SOLUTION	CO ₂	HYGROSCOPIC H ₂ O AT 98.2 PER CENT RELATIVE HUMIDITY
CM.	per cent	per cent	per cent	per cent	per cent	CM.
0-10	1.15	42.31	19.63	33.50	1.13	12.05
10-20	1.65	40.73	22.63	33.26	1.20	11.60
20-30	0.81	40.40	19.61	33.11	1.13	12.57
30-40	0.47	35.84	21.39	36.90	1.15	13.31
40-50	0.36	53.49	16.81	25.10	1.27	10.12
60-70	0.28	62.28	14.32	19.99	0.84	12.44
90-100	0.10	54.34	19.69	22.84	1.03	9.65
110-120	0.08	82.42	6.01	10.47	0.19	5.92
130-140	0.19	41.04	21.86	34.14	0.69	10.66
160-170	0.28	36.09	21.43	41.44	0.86	11.49

* By the A. E. A. method.

TABLE 3
Percentages of moisture at field capacity in plots I and II during low and high water tables

DEPTH	PLOT I				PLOT II			
	February 1948		October 1947		March 1948		October 1947	
	Weight	Volume	Weight	Volume	Weight	Volume	Weight	Volume
CM.	per cent	per cent	per cent	per cent	per cent	per cent	per cent	per cent
0-5	53.1	42.6	45.9	42.7	41.3	40.8	42.2	41.5
5-10	37.3	38.7					37.8	38.5
10-20	28.8	31.4	29.4	32.0	31.6	32.9	30.2	33.3
20-30	28.7	33.7	28.9	32.1	31.2	33.9	30.1	33.9
30-40	27.7	33.8	28.1	38.1	30.8	33.9	31.8	42.9
40-50	19.7	22.9	28.3	34.7				

layers underlain by a sticky layer extending to a depth of 170 cm. The structure is adobe. Plot I is an orchard of mature orange trees. Plot II is cultivated according to the local rotation system. Table 2 shows the mechanical analyses of the different layers of the profile in plot I.

The field capacities (6) of the surface layers of the two plots are given in table 3 with the dates of their estimation.

The irrigation water is measured with a weir constructed by the Hydrological Service, Ministry of Public Works, and found to be correct within 10 per cent of its actual discharge.

A complete record of the atmospheric temperature, relative humidity, wind, and rain is obtained from a meteorological screen in plot I. Daily readings of earth thermometers placed close to the screen are made at 8 a.m.

The water table fluctuates continually within narrow limits in the two plots because of an underground flow from a nearby canal with variable water levels.

TABLE 4

Moisture, pore space, air, and water contents and apparent and real densities in a profile in plot I, at field capacity, October 1947

DEPTH	MOISTURE		APPARENT DENSITY	REAL DENSITY	PORE SPACE, VOLUME	AIR/PS.* $\times 100$	WATER/PS. $\times 100$
	Weight	Volume					
cm.	per cent	per cent	gm./ml.	gm./ml.	per cent		
0-10	45.9	42.7	0.93	2.56	63.7	33	67
10-20	29.4	32.0	1.09	2.71	59.8	46	54
20-30	28.9	32.1	1.11	2.68	58.6	45	55
30-40	28.1	38.1	1.36	2.72	50.0	24	76
40-50	28.3	34.7	1.23	2.77	55.6	38	62
50-60	36.0	44.6	1.24	2.70	54.1	18	82
60-70	39.7	49.4	1.24	2.72	54.4	9	91
70-80	40.3	50.4	1.25	2.66	53.0	5	95

* Ps. = pore space.

The River Nile affects the subsoil water table in the form of a lagged rise during the flood season—August to November; a fall in December, January, and February; and a more or less constant intermediate level from March to July. The whole wave ranges from about 80 cm. to about 200 cm. from the land surface according to yearly changes in the flood height.

Twice, when plot I reached its field capacity, the moisture content and the apparent and real densities of the sequence of layers down to the water table were measured: once when the table was nearest to the surface, in the second week of October 1947, and again when it was near its lowest level, in the fourth week of February 1948. Tables 4 and 5 include the data obtained.

These data show that the water table affected the normal field capacity for an upward distance of about 50 cm., that is, when the level of the table rose to 80 cm. from the surface, the moisture content in the 30-40-cm. layer was increased 4.3 per cent by volume.

The rise of the water table during the flood season, which lasted about 3 months, destroyed almost all the roots that had grown during the months when the level was low. At the February sampling, roots in different stages of decomposition were found below 80 cm. This condition was a result of the sharp swing in the air/water balance toward anaerobic conditions from September to December in this zone.

TABLE 5

Moisture, pore space, air, and water contents and apparent and real densities in a profile in plot I, at field capacity, February 1948

DEPTH	MOISTURE		APPARENT DENSITY	REAL DENSITY	PORE SPACE, VOLUME	AIR/PS * $\times 100$	WATER/PS. $\times 100$
	Weight	Volume					
cm.	per cent	per cent	gm./ml.	gm./ml.	per cent		
0- 5	53.1	42.6	0.80	2.56	68.8	38	62
5- 10	37.3	38.7	1.04	2.56	59.4	35	65
10- 20	28.8	31.4	1.09	2.71	59.8	47	53
20- 30	28.7	33.7	1.17	2.68	56.3	40	60
30- 40	27.7	33.8	1.22	2.72	55.1	39	61
40- 50	19.7	22.9	1.16	2.77	58.1	61	39
50- 60	24.7	27.4	1.11	2.70	58.9	53	47
60- 70	29.1	34.7	1.19	2.72	56.3	38	62
70- 80	34.5	40.7	1.18	2.66	55.6	27	73
80- 90	29.4	38.2	1.30	2.65	50.9	25	75
90-100	29.5	34.5	1.17	2.65	55.8	38	62
100-110	26.3	33.6	1.28	2.65	51.7	35	65
110-120	27.0	35.9	1.32	2.65	50.2	28	72
120-130	37.3	47.3	1.27	2.70	53.0	11	89
130-140	29.6	43.3	1.46	2.70	45.9	6	94
140-150	29.1	41.6	1.43	2.60	45.0	8	92
150-160	29.3	44.2	1.51	2.76	45.3	2	98
160-170	29.0	44.7	1.54	2.78	44.6	0	100

* Ps. = pore space.

LOSSES AND GAINS OF MOISTURE

Plot I

Figure 1 shows the moisture changes from March 1947 to February 1948. The moisture content is expressed in depths of water to make possible combining the results of the added water with the losses from the soil.

The numerical values of losses and gains at the end and at the beginning of every cycle of irrigation are given in table 6. Losses are the total lowering of moisture from the field capacity (4), and gains are the depths of water given through irrigation as obtained from the weir readings. In each of the eight irrigations, excess water added is between 8.2 and 11.4 cm. The total moisture removed is 32.5 cm., and the total added is 113.0 cm., making an apparent excess of 80.5 cm. throughout the year. But a considerable part of this excess is needed to compensate for two other types of moisture losses that are not numerically

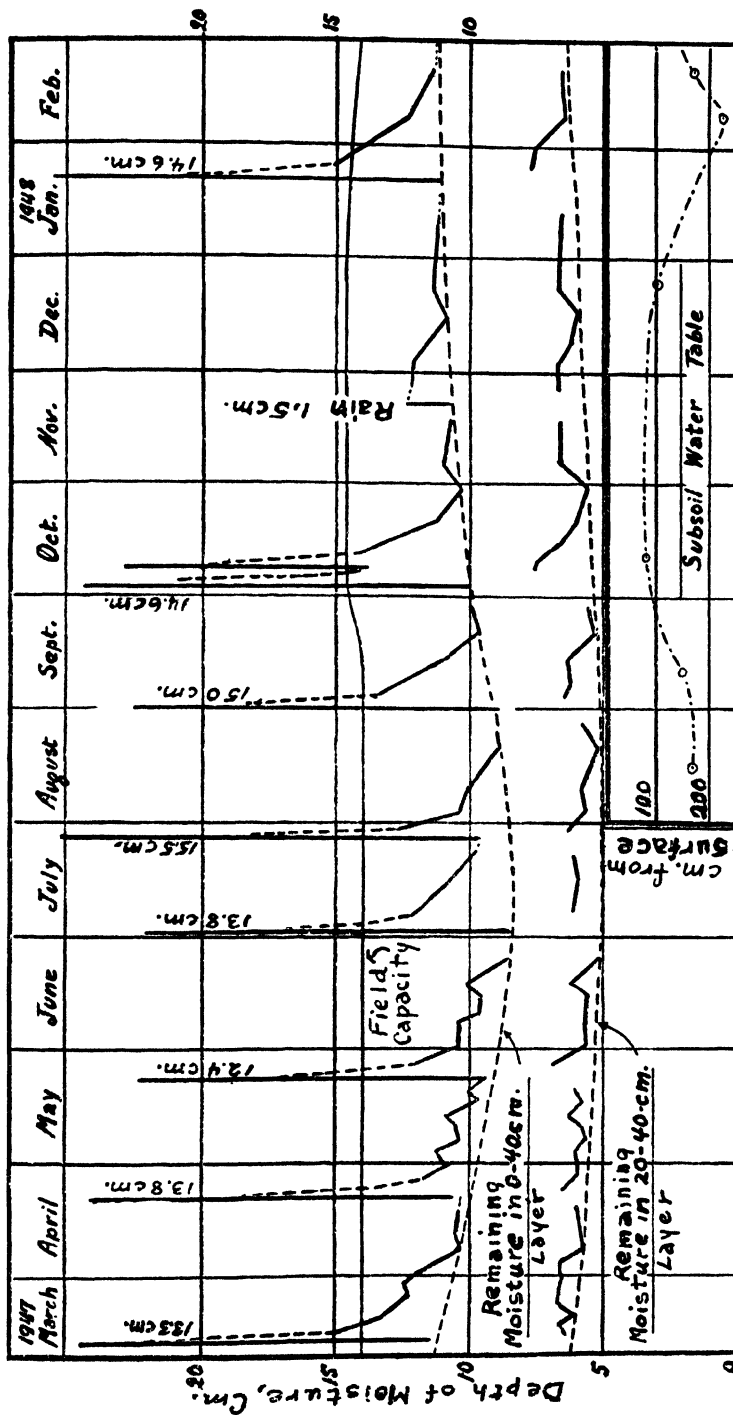


FIG. 1. MOISTURE CHANGES IN PLOT I THROUGHOUT A YEAR, AND WATER-TABLE MOVEMENTS FROM AUGUST TO FEBRUARY

measured in this work, namely, loss by evaporation and absorption from the time of irrigation until the soil reaches field capacity, and loss by evaporation and absorption from the deeper layers of the soil during the irrigation cycles.

When irrigation water is applied, it raises the soil moisture well above the field capacity in the upper 40 cm. After 2 days in summer to 4 days in winter, the moisture falls to the field capacity. During this time about 1.2 cm. is evaporated or consumed by the plants. This amount can be estimated from table 7,

TABLE 6

Gains and losses, as depth of moisture, in the upper 40 cm. of plot I throughout the year

DATA OF IRRIGATION	TOTAL MOIS- TURE BEFORE IRRIGATION	FIELD CAPACITY	MOISTURE REMOVED	MOISTURE ADDED	EXCESS OF IRRIGATION
	CM.	CM.	CM.	CM.	CM.
Mar. 14, 1947	11.4	14.0	2.6	13.3	10.7
Apr. 21, 1947	10.4	14.0	3.6	13.8	10.2
May 23, 1947	10.1	14.0	3.9	12.4	8.5
July 1, 1947	8.4	14.0	5.6	13.8	8.2
July 27, 1947	9.9	14.0	4.1	15.5	11.4
Aug. 31, 1947	9.0	14.0	5.0	15.0	10.0
Oct. 10, 1947	10.1	14.5	4.4	14.6	10.2
Jan. 23, 1948	11.2	14.5	3.3	14.6	11.3
Total.....			32.5	113.0	80.5

TABLE 7

Losses of moisture from the upper 40 cm. of plot I in the first few days after the soil reaches its field capacity

MONTHS	TIME AFTER REACH- ING FIELD CAPACITY	TOTAL MOISTURE	LOSS PER DAY	AVERAGE TEMPERATURE
	days	CM.	CM.	C.°
March	8	12.3	0.21	16.3
April	7	10.9	0.44	20.2
May	6	10.4	0.60	26.8
July	7	11.5	0.36	27.1
July	6	10.3	0.61	27.6
September	9	10.3	0.39	25.2
October	10	11.2	0.33	20.7
January	10	12.4	0.21	12.6

which shows the loss of moisture, in the first few days after the soil reaches its field capacity.

The rest of the added water that remains after compensation for the moisture removed from the upper 40 cm. and the 1.2 cm. that is lost before field capacity is reached, ranges between 7.0 and 10.2 cm. This amount percolates through the soil and raises the moisture content in the sequence of layers to slightly above their capacities. Part of the percolating water is absorbed by the roots, and part causes a general movement and replacement of the capillary water with a final

addition of a few centimeters to the water table. A fair idea of the amount absorbed by the roots or evaporated during the cycle can be gained by studying the moisture content in the 40–50-cm. layer before and after irrigation in April and May, for both months are in a hot period and the water table is low. In both months (table 8), the increase in moisture is less than 1 per cent by volume, that is 0.1 cm. deep, and naturally the losses for each 10-cm. layer of soil will decrease with increasing depth. If, therefore, the water table is at its lowest level, 200 cm., the total loss of moisture from the zone below the upper 40 cm. could not be more than 1.5 cm. This amount will compensate for both evaporated and absorbed moisture. With the rise of the subsoil water table from October to January, the moisture in the zone below the upper 40 cm. increases to well

TABLE 8

Moisture content of the 40–50-cm. layer of plot I before and after irrigation

DATE OF SAMPLING	TIME AFTER IRRIGATION	MOISTURE	
		WEIGHT	VOLUME
	<i>days</i>	<i>per cent</i>	<i>per cent</i>
Apr. 18	35	28.18	34.38
Apr. 26	5	28.83	35.17
May 13	22	28.85	35.49
May 27	4	29.82	36.56

TABLE 9

Maximum moisture losses to be compensated by irrigation water in different seasons

LOSS THROUGH	FEBRUARY TO SEPTEMBER	OCTOBER TO JANUARY
	<i>cm.</i>	<i>cm.</i>
Evaporation before field capacity is reached.....	1.2	1.2
Water removed from 0–40-cm. depth.	5.8	3.0
Water removed from layers below 40 cm.....	1.5	nil
Total ...	8.5	4.2

above the field capacity in the greater part of the profile, and there will be no need, therefore, to allow for any compensation of losses in this zone during these 4 months.

Thus, only about 1.5 cm. of the 7.0 to 10.2 cm. of percolating water is needed in summer for the lower layers, and the rest is added to the water table, causing a temporary rise in its level, of about four times the amount added (1).

The amount of moisture that should be compensated through irrigation must, therefore, include what is lost before the soil reaches field capacity and what is removed from the sequence of layers during the cycle of irrigation. These amounts differ throughout the year, but their maxima lie between 8.5 cm. for summer and 4.2 cm. for winter, as shown in table 9.

In view of this loss and of the range in irrigation water from 12.4 to 15.5 cm.,

it is evident that a notable part of the irrigation water is added to the water table. The water table does not remain high for long because of the permeability of the fine sandy layers in which the water fluctuates in this plot.

Plot II

Cotton and maize were cultivated in plot II. A 67-day fallow period preceded maize.

The moisture changes in plot II were similar to those in plot I. Table 10 shows the moisture gains and losses in the upper 30 cm. in both cotton and maize fields.

TABLE 10

Gains and losses, as depth of moisture, in the upper 30 cm. of plot II throughout the year

DATE OF IRRIGATION	TOTAL MOISTURE BEFORE IRRIGATION	FIELD CAPACITY	MOISTURE REMOVED	MOISTURE ADDED	EXCESS OF IRRIGATION
<i>Cotton field</i>					
1947	cm.	cm.	cm.	cm.	cm.
Apr. 16	8.8	10.8	2.0	7.5	5.5
May 2	8.3	10.8	2.5	17.5	15.0
May 21	7.7	10.8	3.1	14.0	10.9
June 6	7.0	10.8	3.8	9.8	6.0
June 25	6.8	10.8	4.0	9.8	5.8
July 25	6.5	10.8	4.3	11.0	6.7
<i>Maize field</i>					
June 24	4.4	10.8	6.4	20.0	13.6
July 15	7.7	10.8	3.1	18.0	14.9
Aug. 8	7.2	10.8	3.6	11.0	7.4
Aug. 29	7.5	10.8	3.3	10.0	6.7
Sept. 10	8.2	10.8	2.6	8.9	6.3
Sept. 26	7.6	10.8	3.2	9.8	6.6
Oct. 11	8.7	10.8	2.1	11.0	8.9
Total of two fields	...	...	44.0	158.3	114.3

Exceptionally high figures for irrigation water are recorded once in the cotton field (17.5 cm. on May 2) and twice in the fallowed land (20.0 and 18.0 cm. in June and July respectively). These high figures are due, on the one hand, to mulching of the cotton field, and, on the other hand, to deep ploughing of the fallowed land. In these three cases the irrigating time was greatly extended, allowing a greater discharge because of (a) the slow flow of water on the disturbed soil surface and (b) the very dry mulched or ploughed surface layer, which absorbs and holds more moisture because of its loose packing and comparatively wide pore spaces.

When these extremes are excluded, the excess of irrigation water over the

recorded losses ranges from 10.9 to 5.5 cm. The losses that should be compensated from these excessive amounts differ slightly from those of plot I, and allowance for losses from the 30–40-cm. layer should be made.

The moisture losses from the 30–40-cm. layer can be estimated from data on the corresponding layer in plot I. Table 11 records moisture losses from this layer in plot I after a time about equal to that of the average irrigation cycle of plot II. The greatest recorded moisture loss is 0.6 cm., in June. Thus, the maximum water depth needed in summer for the cotton field should include: (a) 1.2 cm. lost before field capacity is reached, (b) 4.3 cm. lost from the upper 30 cm., (c) 0.6 cm. lost from the 30–40-cm. layer, and (d) 1.5 cm. lost from the layers below 40 cm. The total depth, therefore, should be 7.6 cm. instead of the 8.5 cm. for plot I.

On the same basis of calculation, the maize field needs slightly less water during August and September and much less in October; a depth of 7.0 cm. per irrigation suffices to compensate for the total loss in August and September,

TABLE 11

Recorded drop in moisture content in the 30–40-cm. layer of plot I about 3 weeks after irrigation

DATES OF ESTIMATIONS	TIME AFTER IRRIGATION	MOISTURE, BY VOLUME	DROP IN MOISTURE	
			per cent	cm.
1947	days	per cent		
Mar. 17	3	33.63	1.72	0.17
Apr. 4	21	31.91		
Apr. 26	5	33.59	2.79	0.28
May 10	19	30.78		
May 24	4	34.05	5.69	0.57
June 14	22	28.36		
July 29	2	30.77	5.24	0.52
Aug. 20	24	25.53		

whereas only 4.0 cm. is needed in October, because of the effect of the rise in water table on the moisture content in the zone below 40 cm.

Before the fallowing season, the land was occupied by the leguminous fodder *Trifolium*. The plants showed permanent-wilting symptoms when the moisture content fell to 8.8, 17.7, and 18.1 per cent by weight, and to 10.7, 20.8, and 24.6 per cent by volume for every 10-cm. depth. The wilting points, calculated as 1.47 times the hygroscopic coefficient (2), for the three layers are 17.7, 16.1, and 18.5 per cent, respectively, and good agreement is noted between the actual and the calculated values in the 10–20 and the 20–30-cm. layers.

The amount of irrigation water applied after fallowing is about double the ordinary irrigation. Though the moisture removed from the upper 30 cm. is 6.4 cm., it is difficult to say how much of the 20 cm. applied by irrigation is unnecessary for compensating for the total moisture removed from the deeper layers, because no estimate was made of moisture distribution at the end of the fallowing period.

AMOUNTS AND PERCENTAGES OF EXCESS WATER

The previous discussion of moisture gains and losses shows conclusively the excessive irrigation in every case. Table 6 shows that plot I received, in eight irrigation cycles, a total of 113.0 cm. of water, while the total recorded removed moisture was only 32.5 cm.; and table 10 shows that plot II received 158.3 cm. to compensate for a total loss of 44.0 cm. in thirteen irrigation cycles.

TABLE 12
Losses, gains, and excess of irrigation water in 20 cycles

DATES	PLOT	RECORDED LOSS FROM SURFACE LAYERS	LOSS BEFORE REACHING FIELD CAPACITY IS REACHED	MAXIMUM LOSS FROM LOWER LAYERS	TOTAL LOSS	IRRIGA- TION WATER	EXCESS WATER	
		cm.	cm	cm.	cm.	cm.	cm.	per cent*
1947								
Mar. 14	I	2.6	1.2	1.5	5.3	13.3	8.0	60
Apr. 4	II, cotton	2.0	1.2	2.1	5.3	7.5	2.2	29
Apr. 21	I	3.6	1.2	1.5	6.3	13.8	7.5	54
May 2	II, cotton	2.5	1.2	2.1	5.8	17.5	11.7	67
May 21	II, cotton	3.1	1.2	2.1	6.4	14.0	7.6	54
May 23	I	3.9	1.2	1.5	6.6	12.4	5.8	47
June 6	II, cotton	3.8	1.2	2.1	7.1	9.8	2.7	28
June 25	II, cotton	4.0	1.2	2.1	7.3	9.8	2.5	26
July 1	I	5.6	1.2	1.5	8.3	13.8	5.5	40
July 15	I, maize	3.1	1.2	2.1	6.4	18.0	11.6	64
July 25	II, cotton	4.3	1.2	2.1	7.6	11.0	3.4	31
July 27	I,	4.1	1.2	1.5	6.8	15.5	8.7	56
Aug. 8	II, maize	3.6	1.2	2.1	6.9	11.0	4.1	37
Aug. 29	II, maize	3.3	1.2	2.1	6.6	10.0	3.4	34
Aug. 31	I	5.0	1.2	1.5	7.7	15.0	7.3	49
Sept. 10	II, maize	2.6	1.2	2.1	5.9	8.9	3.0	34
Sept. 26	II, maize	3.2	1.2	2.1	6.5	9.8	3.3	34
Oct. 3	I	4.4	1.2	nil	5.6	14.6	9.0	62
Nov. 11	II, maize	2.1	1.2	nil	3.3	11.0	7.7	70
1948								
Jan. 22	I	3.3	1.2	nil	4.5	14.6	10.1	69
Total.....					126.2	251.3	125.1	
Average.....					6.31	12.57	6.26	50

* Of that applied.

When all possible losses of moisture are taken into account, the excess of water is considerably reduced. In table 12, consideration is given to all losses in the two plots, and the actual excess in twenty irrigation cycles is shown. Of the total 251.3 cm. of irrigation water, 126.2 are needed to compensate for all moisture losses, and an excess of 125.1 cm. is added to the water table.

It may be said, therefore, that only half the irrigation water is needed and the other half is wasted. The waste ranges from 26 per cent and 70 per cent of the irrigation water. Generally the waste is least from June to September and most from October to May.

CYCLIC CHANGES IN MOISTURE CONTENT

In the perennially irrigated lands dealt with in this investigation, the water is usually applied when the appearance of the soil, and sometimes of the plants, indicates the need. Thus the period between two successive irrigations is more or less conventionally defined. The system adopted by the Ministry of Public Works for the distribution of water allows 18 days between two irrigations during the low river season, from February to August, and 12 days during the flood season.

Throughout the irrigation cycle of the land under investigation, the maximum loss of moisture is recorded from the surface layer, and the amounts of moisture lost decrease with increasing depth.

The average course of moisture changes in upper four 10-cm. layers of the soil of plot I is shown in figure 2. The curves are drawn from the average results of eight cycles corrected to the average duration of 34 days. Because of difficulty in obtaining samples for moisture estimation immediately after irrigation, the curves were extrapolated to show the state of moisture in the few days following application of water.

The moisture content of the upper 10-cm. layer reaches an average of 48 per cent by weight, that of the 10-20-cm. layer reaches 35 per cent, and those of the 20-30 and 30-40-cm. layers reach 29 and 28 per cent respectively. By the end of the cycle the average moisture contents fall to 13.4, 20.9, 22.3, and 22.8 per cent for each of the four layers respectively.

Between the ninth and the eleventh day after irrigation the moisture becomes almost equal in the four layers, after which the surface layer loses moisture at a daily rate of about 0.9 per cent for 9 days, followed by a diminishing rate, which becomes insignificant when the moisture approaches the hygroscopic limits. The moisture in the underlying layers is lost at a slower rate, which becomes very low after 25 days.

Ratios of the actual moisture to the wilting coefficient in each of the four layers along the average cycle give a clearer idea of the accessibility of the soil moisture to plants. Figure 3 shows these ratios. Though this basis of interpretation does not change greatly the behavior shown in figure 2, it shows that the moisture in the surface layer falls below the wilting point after about 18 days on the average and that the moisture in the 30-40-cm. layer approaches the wilting point more closely than the two overlying layers, which must be due to absorption by the flourishing root system in this zone.

These changes of moisture through the cycle of irrigation are almost similar in both the cotton and maize fields, the only difference being the duration of cycle.

Figure 4 presents the average moisture contents of the upper 30 cm. of the orchard, cotton, and maize soils through their cycles of irrigation. It shows that the rate of loss of moisture is slower from the orchard soil than from the cotton and maize fields. The initial soil moisture contents of both the orchard and the maize field are almost equal; that of the cotton field is about 2 per cent lower. Both orchard and maize field soils lose their moisture at a similar rate for about 6 days, after which the orchard soil dries more slowly, reaching a moisture content of 20 per cent in 25 days in comparison with 17 days for the maize field. Moisture is lost slightly more rapidly in the cotton field than in the maize field for the

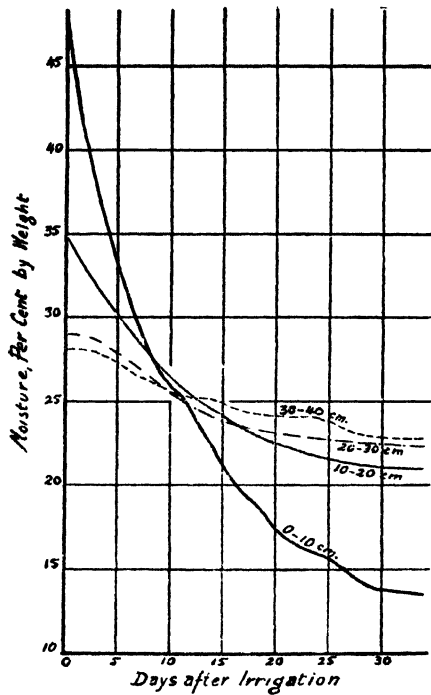


FIG. 2

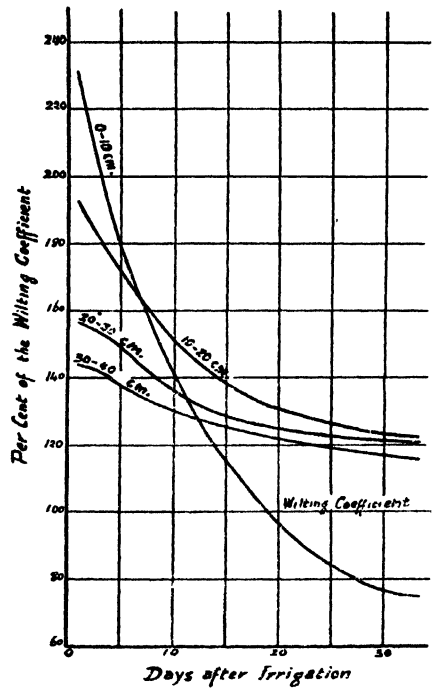


FIG. 3

FIG. 2. AVERAGE COURSE OF MOISTURE CHANGES IN FOUR LAYERS OF THE SOIL OF PLOT I
 FIG. 3. RATIOS OF MOISTURE TO WILTING COEFFICIENT IN FOUR LAYERS OF SOIL IN PLOT I

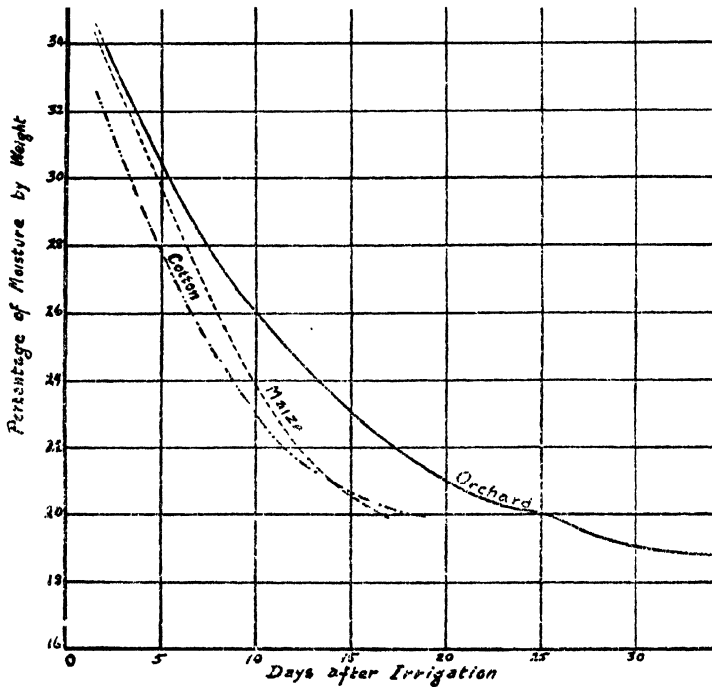


FIG. 4. AVERAGE MOISTURE CONTENTS OF THE UPPER 30 CM. IN PLOT I AND IN THE COTTON
 AND MAIZE FIELDS OF PLOT II THROUGHOUT THEIR IRRIGATION CYCLES

first 4 days, then the rate decreases comparatively; as a result, moisture in the cotton field reaches the 20 per cent level 2 days later than in the maize field and 7 days earlier than in the orchard.

TABLE 13

Moisture removed from upper 10 and 30 cm. of soil and average atmospheric humidity and temperature of through 26 irrigation cycles

PLOT	DATES OF IRRIGATION AND LAST MOISTURE ESTIMATION	LENGTH OF CYCLE	MOISTURE REMOVED FROM 0-10 CM.	MOISTURE REMOVED FROM 0-30 CM.	AVERAGE RELATIVE HUMIDITY	AVERAGE TEMPER- ATURE
		<i>days</i>			<i>per cent</i>	<i>C.°</i>
I, Orchard	Feb. 1-Mar. 14	42	1.9	2.3	83.6	13.9
I, Orchard	Mar. 14-Apr. 18	36	2.5	3.3	80.3	18.4
II, Cotton	Mar. 26-Apr. 12	18	1.8	2.0	79.6	20.1
II, Fodder	Mar. 28-Apr. 12	16	1.4	1.8	79.6	20.1
II, Cotton	Apr. 16-26	11	2.0	2.5	74.5	18.5
II, Fallow	Apr. 18-May 10	23	1.8	2.8	73.0	20.5
I, Orchard	Apr. 21-May 20	30	2.6	3.5	67.0	22.1
II, Cotton	May 2-17	16	2.6	3.1	63.2	22.5
II, Cotton	May 21-June 4	15	2.5	3.8	62.5	25.7
I, Orchard	May 23-June 28	37	3.0	4.8	65.2	26.0
II, Cotton	June 6-24	19	2.6	4.0	66.4	26.1
II, Maize	June 24-July 13	20	2.4	3.1	71.5	26.9
II, Cotton	June 25-July 11	17	2.7	4.2	71.7	26.8
I, Orchard	July 1-22	22	2.6	4.1	70.5	27.8
II, Cotton	July 13-24	12	2.7	4.3	70.4	28.4
II, Maize	July 15-Aug. 3	20	2.5	3.6	72.9	27.9
II, Cotton	July 25-Aug. 3	10	2.0	2.9	75.2	27.4
I, Orchard	July 27-Aug. 27	32	2.8	4.3	77.9	27.2
II, Cotton	Aug. 7-21	15	1.9	3.1	76.3	27.0
II, Maize	Aug. 8-27	20	2.3	3.3	78.1	27.0
II, Maize	Aug. 29-Sept. 6	9	1.8	2.6	77.8	26.2
I, Orchard	Aug. 31-Sept. 20	21	2.5	3.9	77.2	24.7
II, Maize	Sept. 9-24	16	2.2	3.2	74.2	23.6
II, Maize	Sept. 26-Oct. 7	12	1.3	2.1	83.1	23.7
I, Orchard	Oct. 8-Jan. 10	95	2.1	2.8	84.0	16.5
I, Orchard	Jan. 22-Feb. 21	31	1.7	2.6	80.8	12.5
Average		24	2.24	3.23	74.5	23.4

SEASONAL CHANGES IN MOISTURE REMOVED

From data already presented, it is clear that moisture remaining in the soil decreases in summer and increases in winter, and that the maximum total loss of moisture occurs in June and July and the minimum from October to April.

Table 13 shows the moisture removed from the upper 10 cm. and the upper 30 cm. of soil, and the average relative humidity and temperature of the atmosphere during the cycle of irrigation in the two plots. The long irrigation cycles of plot I account for the greater moisture losses, in comparison with plot II.

Statistical analysis of the results in table 13 shows that the effect of atmospheric

relative humidity is more dominant than that of temperature on the 0-10-cm. surface layer, but the total loss from the surface 30 cm. is affected more by the temperature of the atmosphere (table 14). When the results of plot I, which has a longer irrigation cycle, are taken separately, the effect of temperature is found to be much more dominant than that of relative humidity (table 15).

Thus, it may be said that, of the environmental factors governing evaporation, heat is most dominant. Bulk air movement due to temperature gradients between the different layers of the drying soil is one of the chief causes of moisture losses (3) especially from the upper layers of soil. Records made in 1922 (5) show that the maximum and minimum temperatures of the fallowed soil at Giza—average for the week of July 22 to 29—were 63.3° and 22.2° for the surface, 50.3° and 27.6° at a depth of 5 cm., 41.0° and 30.5° at a depth of 10 cm., 37.0° and 31.5° at

TABLE 14

Correlation coefficients between moisture removed from soil and atmospheric temperature and relative humidity in 26 irrigation cycles

	RELATIVE HUMIDITY	TEMPERATURE
Moisture removed from 0-10-cm. layer.	$r = -0.65$	$r = +0.49$
Moisture removed from 0-30-cm. layer	$r = -0.56$	$r = +0.61$

TABLE 15

Correlation coefficients between moisture removed from soil and atmospheric temperature and relative humidity in long irrigation cycles

	RELATIVE HUMIDITY	TEMPERATURE
Moisture removed from 0-10-cm. layer	$r = -0.74$	$r = +0.89$
Moisture removed from 0-30-cm. layer	$r = -0.84$	$r = +1.00$

15 cm., 35.3° and 31.6° at 20 cm., and a constant 33.3° at 30. cm. The effect of these high temperatures, added to the accelerated transpiration from the plants in summer, explains the seasonal variations in moisture removed.

On November 22 and 23 a rainfall of 1.5 cm. raised the moisture content from 4.39 to 5.65 cm. in the upper 0-30-cm. layers of soil, but rainfalls of less than 0.2 cm. had no effect on the soil moisture.

SUMMARY

This study shows that moisture gains through irrigation are much greater than losses from the soil on two plots in Giza District, Egypt.

In the orchard, which has a long irrigation cycle, the maximum loss, both recorded and deduced, is 8.3 cm. and the minimum is 5.3 cm. The irrigation water ranges from 15.5 cm. to 12.4 cm. In eight irrigations the excess of water is between 10.1 and 5.5 cm.

In cotton and maize fields the maxima of moisture removed are 7.6 and 7.7 cm., and the minima are 5.3 and 3.3 cm. Of the amounts of irrigation water, which range between 8.9 and 18.0 cm., 11.7 to 2.5 cm. is not needed and is added to the water table. The percentages of excess irrigation water range from 26 to 70, averaging 50 in 20 records.

Two types of moisture changes are evident: cyclic and seasonal.

The cyclic changes occur between two successive applications of water. After irrigation of the land, the moisture content reaches a maximum in the surface layers, especially the upper 10 cm. The average moisture contents of the upper four 10-cm. layers of the soil of plot I at the beginning of the cycle are 48, 35, 29, and 28 per cent by weight. By the end of the 34-day cycle, the moisture falls to 13.4, 20.9, 22.3, and 22.8 per cent for the four layers. An almost similar behavior is noted in both cotton and maize cycles, the only difference being in the duration of the cycle.

Moisture is lost at different rates from the soil supporting the three crops. The rate is slowest in the orchard, and fastest in the maize field.

Study of the average moisture contents throughout the cyclic changes shows that in the surface 10 cm. the moisture fall below the wilting point after about 18 days, whereas in the underlying layers, it does not reach the wilting point even after the long 34-day cycle in plot I.

The seasonal changes are apparent in the total amount of moisture removed from the surface layers. The highest recorded values are those of plot I, in May, and lowest are those of the maize field, in October.

Statistical analyses show that the amount of moisture removed from the surface 10 cm. of soil is correlated negatively with the average relative humidity of the atmosphere, the correlation coefficient being -0.65 ; the total moisture removed from the surface 30 cm. of soil is positively correlated with the average temperature, the correlation coefficient being $+0.61$.

In plot I, with the long irrigation cycle, the average temperature is the dominant factor in removal of moisture, as the correlation coefficient between moisture removed from the surface 30 cm. and the average temperature is $+1.00$.

REFERENCES

- (1) BALLS, W. L., AND ZAGHLOUL, M. A. 1932 Water table movements in a farm in Egypt. *Roy. Soc. [London] Phil. Trans. (B)* 221: 335-375.
- (2) BRIGGS, L. J., AND SHANTZ, H. L. 1912 The wilting coefficient for different plants and its indirect determination. U. S. Dept. Agr. Bur. Plant Indus. Bul. 230.
- (3) FISHER, E. A. 1927 Some factors affecting the evaporation of water from soil: III. *Jour. Agr. Sci.* 17: 407-419.
- (4) STAPLE, W. J., AND LEHANE, J. J. 1944 Estimation of soil moisture conservation from meteorological data. *Soil Sci.* 58: 177-193.
- (5) TAYLOR, E. M., AND BURNS, A. C. 1924 Soil temperatures during the Sharāqi period and their agricultural significance. Egypt Min. Agr., Tech. and Sci. Serv. Bul. 31.
- (6) VEIHMEYER, F. J., AND HENDRICKSON, A. H. 1931 The moisture equivalent as a measure of field capacity of soils. *Soil Sci.* 32: 181-193.
- (7) SIMAIKA, Y. M. 1940 Tilling Asswan Reservoir in the future. Egypt Min. Pub. Works Phys. Dept. Paper 42.

CELLULOSE-DECOMPOSING POWER IN RELATION TO REACTION OF SOILS¹

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Waksman and Heukelekian (2) concluded, from their studies and the results of other investigators, that there is no correlation between soil reaction and the power of the soil to decompose cellulose. They emphasized the fact that fungi which take an active part in decomposition of cellulose will thrive readily even under the most acid soil conditions, in which cultivated plants will barely grow at all.

Their studies on limed and unlimed field plot soils showed that addition of available nitrogen, which had little effect on soil reaction, increased the cellulose-decomposing power of the unlimed soils to a degree comparable with that of the limed soils. The authors concluded, therefore, that the amount of cellulose decomposed in soils is dependent on the concentration of available nitrogen, independent of soil reaction.

Early studies of the authors of the present paper (4) showed that soil acidity had a definite controlling influence on the rate of cellulose decomposition. These studies, which gave results contrary to the findings of Waksman and Heukelekian, were made on soils where soil reaction was the only variable other than the relatively small amounts of added lime. Additions of available nitrogen to a series of the cellulose-treated soils of reaction below pH 6.0 increased the cellulose-decomposing power by 27 per cent compared with an increase of 35 per cent when nitrogen was added to the soils of reactions above pH 6.0. In no case did additions of available nitrogen to the acid soils result in an increase in their cellulose-decomposing power comparable with that of the soils of pH 7.1 and 7.4.

Results based on studies of field plot soils selected on the basis of differences in soil reaction as reported by Waksman and Henkelekian, do not represent true measures of the relative effects of soil acidity upon microbiological activity. As the result of differences in field treatments, such soils may differ widely in buffer capacity and other variables known to influence the activities of soil microorganisms.

In the authors' early studies (4) only six pH values were included. The present paper reports more extensive experiments, including both laboratory and field plot soils.

EXPERIMENTAL PROCEDURE

The rate of cellulose decomposition in relation to soil reactions is based on studies of three different acid soils treated with $\text{Ca}(\text{OH})_2$ in amounts shown in

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tables 1 to 3. Soil 1 was prepared by treating Hagerstown silt loam soil of pH 7.4 with an excess of sulfur and incubating at optimum moisture content for 4 months. Soil 2 was taken from plot 32, tier 1, of the Jordan series of field plots, which had received heavy applications of ammonium sulfate for 40 years (1). Soil 3 was taken from plot 6, field B, of the Snow Shoe pasture experiment and represents an infertile mountainland silt loam of the DeKalb Series (5).

Each soil was divided into eleven 250-gm. portions, each of which received 42 mgm. of available nitrogen (NaNO_3). The portions of soil 3 received, in addition, 50 mgm. of K_2HPO_4 . Cellulose (ground filter paper) was added to each portion of the three soils at the rate of 1.25 gm. to 250 gm. of air-dried soil. A second series was included in which the soil portions received the same treatments except that no cellulose was added. Each of the 66 portions of soil was made up to 55 per cent of the maximum water-holding capacity and incubated for 14 days in the manner previously described (4, 6).

The cellulose decomposed is based on the CO_2 recovered at 2- and 3-day intervals, in excess of that recovered from the soils to which no cellulose was added. The CO_2 reported in tables 1 to 3 represents the totals recovered in 14 days. In the soils prepared in the manner indicated, soil reaction is the only variable other than the relatively small amounts of added lime.

The data obtained from the specially prepared laboratory soils are compared with results obtained from similar studies of Jordan field plot soils in which variables in addition to that of soil reaction are present. The cellulose-decomposing power of the Jordan soils was determined without addition of available nitrogen in order that nitrogen might be included as one of the several variables.

Jordan field plot data presented include also the relative cellulose-decomposing power of 20 soils of tiers 1 and 4 in relation to residual soil organic matter and nitrifying capacity (6). The plot soils arranged in pairs of the same pH, serve to emphasize the controlling influence of organic matter, a major factor of buffer capacity, on the activities of soil microorganisms, as measured by cellulose decomposition and rate of nitrification (4, 6). The difference in the relationship between cellulose decomposition and soil reaction of the laboratory and field plot soils, is emphasized by the correlation data presented in table 7.

The Jordan field plot treatments included in tables 5 and 6 were used from 1881 to 1922. Beginning in 1923 (1) CaO was discontinued on plots 22 and 23 and CaSO_4 on plot 33 of tier 4. Since 1923, plot 22 has received 6 tons of manure per acre reinforced with 30 pounds of P_2O_5 . All plots included in tables 4 and 6 of tier 4, except plots 22 and 23, have received applications of limestone since 1923 in amounts indicated by frequent lime requirement determinations (3). The field plot treatments of tier 1 have been continued without change since 1881. No lime has been applied except on plots 13, 22, and 23. The field plot data presented are based on soil samples taken from tier 1 in 1928 and from tier 4 in 1931, at the end of 47 and 50 years of continuous treatments.

The methods used for determining organic matter, cellulose-decomposing power, and nitrifying capacity were described in detail in previous papers (4, 6). The pH was determined electrometrically with the glass electrode (10 gm. soil in 10 ml. H_2O).

TABLE 1
Cellulose-decomposing power of soil 1 in relation to soil reaction

Ca (OH) ₂ ADDED	FINAL REACTION	CO ₂ RECOVERED IN 14 DAYS		
		Soil + N	Soil + N + cellulose	CO ₂ from cellulose*
<i>per cent</i>	<i>pH</i>	<i>mgm.</i>	<i>mgm.</i>	<i>mgm.</i>
0.50	7.6	459	1167	708
0.45	7.2	453	1293	840
0.40	7.1	438	1253	815
0.35	6.6	409	1187	778
0.28	6.2	397	1160	763
0.22	5.8	306	986	680
0.16	5.5	265	857	592
0.10	4.7	244	822	578
0.04	4.2	189	620	431
0.02	4.0	174	588	414
0	3.8	184	614	430

* By difference.

TABLE 2
Cellulose-decomposing power of soil 2 in relation to soil reaction

Ca (OH) ₂ ADDED	FINAL REACTION	CO ₂ RECOVERED IN 14 DAYS		
		Soil + N	Soil + N + cellulose	CO ₂ from cellulose*
<i>per cent</i>	<i>pH</i>	<i>mgm.</i>	<i>mgm.</i>	<i>mgm.</i>
0.50	7.4	656	1294	638
0.45	7.2	684	1432	748
0.40	6.9	650	1382	732
0.35	6.6	578	1276	698
0.28	6.2	559	1254	695
0.22	5.7	469	1117	648
0.16	5.5	441	1094	653
0.10	5.0	431	1111	680
0.04	4.6	391	999	608
0.02	4.4	369	919	550
0	4.3	362	900	538

* By difference.

TABLE 3
Cellulose-decomposing power of soil 3 in relation to soil reaction

Ca (OH) ₂ ADDED	FINAL REACTION	CO ₂ RECOVERED IN 14 DAYS		
		Soil + N + K ₂ HPO ₄	Soil + N + K ₂ HPO ₄ + cellulose	CO ₂ from cellulose*
<i>per cent</i>	<i>pH</i>	<i>mgm.</i>	<i>mgm.</i>	<i>mgm.</i>
0.50	7.4	502	1124	622
0.45	7.2	513	1262	749
0.40	6.9	476	1155	679
0.35	6.5	413	1060	647
0.28	6.1	367	1018	651
0.22	5.6	306	927	621
0.16	5.3	272	843	571
0.10	4.8	259	908	649
0.04	4.5	228	834	606
0.02	4.4	219	800	581
0	4.3	237	838	601

* By difference.

RESULTS

Laboratory soils

The rates of cellulose decomposition in relation to soil reaction of soils 1, 2, and 3 are shown in tables 1, 2, and 3. These data, based on soils in which reaction is the only variable other than the relatively small amounts of added lime, show conclusively that pH 7.2 is the optimum soil reaction for cellulose decomposition. When the experimental error is considered (4), the cellulose CO₂ recovered at pH 7.2 from each of the three soils is significantly higher than that shown for the other ten pH values. Table 7 shows that significant correlations beyond the 1 per

TABLE 4

Cellulose-decomposing power of Jordan field plot soils in relation to soil reaction

TIER 1—1881-1928					TIER 4—1881-1931				
Plot No.	Soil Reaction	CO ₂ recovered in 14 days			Plot No.	Soil Reaction	CO ₂ recovered in 14 days		
		Soil	Soil + Cellulose	CO ₂ from Cellulose*			Soil	Soil + Cellulose	CO ₂ from Cellulose*
	pH	mgm.	mgm.	mgm.		pH	mgm.	mgm.	mgm.
22	7.8	258	860	602	22	7.8	268	766	498
23	7.8	173	462	289	23	7.8	175	574	399
5	6.4	305	684	379	14	7.8	190	436	246
14	6.3	185	506	321	36	7.6	227	709	482
36	6.2	213	619	406	16	7.3	329	934	605
7	6.0	308	645	337	1	7.2	217	595	378
33	5.9	197	509	312	8	7.1	201	567	366
35	5.8	342	819	477	20	7.0	337	983	646
12	5.7	371	804	433	19	6.9	328	901	573
15	5.5	281	894	613	5	6.6	233	672	439
20	5.3	351	974	623	27	6.4	277	819	542
18	5.2	340	878	538	30	6.3	258	853	595
10	5.1	294	690	396	10	6.1	267	819	552
17	5.0	279	679	400	31	5.8	242	860	618
30	4.8	279	626	347	32	5.6	264	877	613
31	4.4	297	805	508	25	5.4	272	699	427

* By difference.

cent level exist between soil reaction and the cellulose-decomposing power of the three soils. The results are in accord with the earlier studies cited (4) but are entirely contrary to the conclusion of Waksman and Heukelekian (2) based on their studies and the results of other investigators.

Field plot soils

The data dealing with the cellulose-decomposing power of the Jordan field plot soils in relation to soil reaction are presented in table 4. The results with the field plot soils, in which variables other than soil reaction are present, are entirely different from those obtained from the laboratory soils. There is no relationship between soil reaction and the cellulose-decomposing power of the

plot soils. Thus, on tier 1, maximum cellulose CO_2 was recovered from the plot soil of pH 5.3. On the other hand, table 3 shows that the cellulose CO_2 recovered from laboratory soil 3 at pH 5.3 was only 76 per cent of that recovered at pH 7.2. On tier 4, the maximum cellulose decomposition occurred at pH 7.0.

TABLE 5

Cellulose-decomposing power of Jordan field plot soils of tier 1 in relation to soil organic matter and nitrifying capacity

PLOT NO.	FIELD PLOT TREATMENTS	SOIL REACTION	PERCENTAGE RELATION*		
			CO_2 from cellulose	Organic matter	Nitrifying capacity
		pH	per cent	per cent	per cent
22	CaO + 6 tons manure	7.8	97	99	82
23	CaO	7.8	46	74	66
3	P	6.3	55	68	73
14	Check	6.3	52	72	71
36	Check	6.2	65	91	73
4	K	6.2	57	68	74
33	CaSO_4	5.9	50	72	70
1	Check	5.9	38	58	80
35	PK + 30 N	5.8	77	85	82
13	CaSO_4	5.8	49	67	61
15	PK	5.5	98	85	98
28	PK + 72 N	5.5	72	81	66
20	10 tons manure	5.3	100	100	95
25	PK	5.3	85	75	66
18	8 tons manure	5.2	87	99	100
11	PK + 72 N	5.2	66	78	97
21	PK + 72 N	5.1	74	99	82
10	PK + 48 N	5.1	64	80	73
17	PK + 24 N	5.0	64	96	78
19	PK + 48 N	5.0	59	83	53

* Highest value taken as 100.

On both tiers 1 and 4, the highest values for cellulose decomposition occurred on plot 20, which receives 10 tons of manure applied to each corn and wheat crop.

The explanation for the differences in relationship between soil reaction and cellulose decomposition of the laboratory and field plot soils is found in the data presented in tables 5 and 6. In every case, with one exception, the higher values for cellulose decomposition occur in plot soils of higher organic matter content,

TABLE 6

Cellulose-decomposing power of Jordan field plot soils of tier 4 in relation to soil organic matter and nitrifying capacity

PLOT NO.	FIELD PLOT TREATMENTS	SOIL REACTION	PERCENTAGE RELATION*		
			CO ₂ from cellulose	Organic matter	Nitrifying capacity
		pH	per cent	per cent	per cent
22	CaO + 6 tons manure	7.8	77	99	85
23	CaO	7.8	62	71	62
12	PK + 30 N	7.6	81	82	58
36	Check	7.6	75	81	65
33	CaSO	7.1	66	78	57
8	Check	7.1	57	63	48
20	10 tons manure	7.0	100	100	100
24	Check	7.0	74	73	58
18	8 tons manure	6.9	95	98	95
19	PK + 48 N	6.9	89	89	87
3	P	6.8	63	67	48
4	K	6.8	45	60	39
35	PK + 30 N	6.7	96	99	81
6	NK	6.7	64	66	59
21	PK + 72 N	6.6	91	86	70
5	P + 30 N	6.6	68	73	55
26	PK + 24 N	6.5	90	83	70
7	PK	6.5	73	80	60
9	PK + 48 N	6.3	93	90	70
30	PK + 24 N	6.3	92	85	73

* Highest value taken as 100.

TABLE 7

Correlation coefficients (r) of cellulose-decomposing power with soil reaction (pH), soil organic matter, and nitrifying capacity

VARIABLES CORRELATED	N	r
Soil reaction (pH), soil 1.....	11	.93**
Soil reaction (pH), soil 2.....	11	.83**
Soil reaction (pH), soil 3.....	11	.92**
Soil reaction (pH), plot soils, tier 1.....	16	-.21†
Soil reaction (pH), plot soils, tier 4.....	16	-.45†
Soil organic matter, plot soils, tier 1.....	16	.69**
Soil organic matter, plot soils, tier 4.....	16	.89**
Nitrifying capacity, plot soils, tier 1.....	16	.52*
Nitrifying capacity, plot soils, tier 4.....	16	.86**

* Significant beyond 5 per cent level.

** Significant beyond 1 per cent level.

† No significant correlations.

irrespective of soil reaction. A similar relationship is shown to exist between the nitrifying capacity and cellulose-decomposing power of the 20 pairs of plot soils.

The correlation data in table 7 show that no significant correlation exists between soil reaction and the rate of cellulose decomposition of the field plot soils. Significant correlations, however, are shown to exist between the cellulose-decomposing power of the plot soils and their organic matter content and their nitrifying capacity.

These data are in accord with the results of other investigators (2) concerning the influence of buffer capacity and other variables on the rate of cellulose decomposition of field plot soils. The statement of Waksman and Heukelekian (2), made without reservation, that there is no correlation between the cellulose-decomposing power of soils and soil reaction, applies only to soils in which variables other than soil reaction are present.

SUMMARY

Studies of cellulose-decomposing power in relation to soil reaction, included both laboratory and Jordan field plot soils. In the former, soil reaction was the only variable other than the relatively small amounts of added lime. The latter soils included a number of variables other than soil reaction. Soil organic matter, as a measure of buffer capacity, and relative nitrifying capacity were the only variables included in the data presented.

Significant correlations beyond the 1 per cent level were found to exist between soil reaction and cellulose-decomposing power of the laboratory soils. The maximum cellulose-decomposition of each of the three soils occurred at pH 7.2.

No significant correlation was found between soil reaction and cellulose-decomposing power of the field plot soils. Significant correlations, however, were found to exist between cellulose-decomposing power and organic matter content and between cellulose-decomposing power and nitrifying capacity.

REFERENCES

- (1) NOLL, C. F., GARDNER, F. G., AND IRVIN, C. J. 1931 Fiftieth anniversary of the general fertilizer tests. *Pa. Agr. Exp. Sta. Bul.* 264: 1-24.
- (2) WAKSMAN, S. A., AND HEUKELEKIAN, O. 1924 Mineralogical analysis of soils as an index of soil fertility: VIII. *Soil Sci.* 17: 275-291.
- (3) WHITE, J. W. 1931 The effect of ammonium sulfate on soil reaction. *Jour. Amer. Soc. Agron.* 23: 871-877.
- (4) WHITE, J. W., HOLBEN, F. J., AND JEFFRIES, C. D. 1934 Influence of soil acidity upon the decomposition of organic matter in soils. *Soil Sci.* 37: 1-14.
- (5) WHITE, J. W., ET AL. 1939 Fertility studies on DeKalb-soil. *Pa. Agr. Exp. Sta. Bul.* 370: 1-48.
- (6) WHITE, J. W., ET AL. 1949 Correlation of microbiological and chemical soil data with crop yields of the Jordan soil fertility plots. *Soil Sci.* 67: 279-285.

EFFECTS OF VARIATIONS IN N AND P NUTRITION ON RENEWAL OF GROWTH IN TRANSPLANTED TOMATO SEEDLINGS¹

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This investigation into the effect of varied nitrogen and phosphorus concentrations on the degree of resistance to wilting and on growth resumption of transplanted tomato seedlings was carried on in hopes of alleviating a very pressing problem recently confronting New Jersey tomato growers. For the last 15 years it has been a practice among New Jersey farmers to obtain their tomato seedlings from commercial seedbeds in the southern states, particularly Georgia. This practice derives from the low cost and the facility with which tomato seedlings can be field-grown in the South as compared with local greenhouse production. Considerable economic loss, however, has been sustained, aside from loss due to disease, from the unreliability of these southern grown seedlings. Many of them are affected so adversely by the injurious conditions of handling and shipping that they are incapable of resuming normal growth when transplanted into the field. Manns (13), in dealing with the problem from the plant pathological viewpoint, presents evidence that improvement in methods of "heeling in" and handling may result in an improvement in the tomato stand. Results from work in this laboratory have indicated that varying the concentrations of nitrogen and phosphorus in the nutrient solution produces varying responses within the seedlings to conditions simulating commercial handling and transportation. Seedlings receiving low phosphorus and nitrogen supplies were best able to resist wilting when pulled and allowed to lie in the sun. Ultimately, it was concluded that seedlings grown in nutrient solutions low in phosphorus and with moderate nitrogen showed the greatest ability to resume rapid growth after severe and prolonged exposure to commercial handling conditions.

Many of the concepts involving the relation between nitrogen and carbohydrates are not new. MacGillivray (12), in speaking of tomato and other plants grown with low nitrogen, applied the terms "nitrogen-starved" and "carbohydrate-high plants" synonymously. Kraus and Kraybill (9) presented extensive data to show that starch accumulation in tomato stems accompanies nitrogen deficiency. Jassen (8), also, in working with tomato plants, found that the starch content was highest in low-nitrogen plants, as did Foster (4), Nightingale *et al.* (14) and Watts (21). This accumulation of carbohydrates is interpreted as the result of decreased demand by the plant for carbohydrates for cell synthesis and for energy purposes, when nitrogen is deficient.

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That phosphorus is related in some way to nitrogen assimilation was pointed out by MacGillivray (12) when he observed that phosphorus-deficient and nitrogen-deficient plants had somewhat similar external characteristics; namely, stiffening of stems, stunting of growth, and appearance of anthocyanins in the leaves. Kraybill (10) also presented evidence that symptoms of phosphorus deficiency were very similar to those of nitrogen deficiency.

The object of this experiment was to study the renewal of growth of transplanted tomato seedlings produced in sand culture with various nutrient levels of nitrogen and phosphorus.

METHODS

Cultural methods

Uniform Marglobe tomato seeds were sown in washed quartz sand and supplied with dilute complete nutrient solution on June 27, 1945. Eleven days later, after the appearance of the first true leaves, 60 uniform seedlings were selected and transplanted to washed and HCl- and NaOH-treated quartz sand in glazed earthenware pots, three plants per pot, to be treated according to the experimental plan in table 1. The cultures were flushed daily with about 500 ml. of nutrient solution, later referred to as "a standard solution," of the following composition: $\text{Ca}(\text{NO}_3)_2 \cdot 4\text{H}_2\text{O}$, 0.0045*M*; KH_2PO_4 , 0.00225*M*; K_2SO_4 , 0.00056*M*; MgSO_4 , 0.00225*M* with trace amounts of B, Mn, Zn, and Fe. On July 19 all cultures were started on treatment solutions (table 1) by the constant drip method of Shive and Stahl (18) using approximately 2 liters of solution per day for each pot. The plants were harvested August 13. Two seedlings from each treatment were separated into roots and tops. The tops were weighed and measured for stem height, and tissue samples of tops for analyses of nitrogen, phosphorus, and carbohydrate were placed in an oven at 70°C. A small section of the lower part of the stem from one of these plants in each treatment was preserved in a mixture of formalin (5 per cent), acetic acid (5 per cent), and alcohol (90 per cent) for subsequent microscopic starch examination. The third seedling from each nutrient treatment was pulled from the sand without separation of roots from tops, exposed to the bright sun at noon for 1½ hours, and then observed for degree of resistance to wilting. These seedlings were then packed in bundles with moist sphagnum moss around the roots. The bundles were wrapped in brown paper and placed in a half-bushel basket, with ordinary weeds surrounding the bundles, to ensure a tight fit (5). The baskets were then placed in storage in the laboratory basement for 5 days. The seedlings were then unpacked, examined for response to storage conditions including root development, and transplanted to their original pots after the lateral roots were clipped off close to the main taproot. All cultures were then treated with the original standard nutrient solution.

Observations were made on extent of recovery of turgidity and growth resumption. Ten days after transplanting the plants were harvested. They were examined for renewed root development, and data were recorded on green weight of tops and stem height. The plant tissues were then prepared for chemical analyses.

TABLE 1

Molecular concentrations of nutrient solutions for varied N and P treatments of tomato seedlings prior to storage and transplanting*

N LEVELS	NUTRIENT SALTS	SOLUTION CONCENTRATION			
		0.5 ppm. P	2.5 ppm. P	5 ppm. P	50 ppm. P
ppm.		M	M	M	M
10	KH ₂ PO ₄	.000016	.000080	.000160	.001125
	Ca(NO ₃) ₂	.000357	.000357	.000357	.000357
	K ₂ SO ₄	.001110	.001045	.000960	—
	MgSO ₄	.002250	.002250	.002250	.002250
	CaCl ₂	.004140	.004140	.004140	.000475
	NaH ₂ PO ₄	—	—	—	.000475
50	KH ₂ PO ₄	.000016	.000080	.000160	.001125
	Ca(NO ₃) ₂	.001785	.001785	.001785	.001785
	K ₂ SO ₄	.001110	.001045	.000960	—
	MgSO ₄	.002250	.002250	.002250	.002250
	CaCl ₂	.002715	.002715	.002715	.002715
	NaH ₂ PO ₄	—	—	—	.000475
100	KH ₂ PO ₄	.000016	.000080	.000160	.001125
	Ca(NO ₃) ₂	.003750	.003570	.003570	.003570
	K ₂ SO ₄	.001110	.001045	.000960	—
	MgSO ₄	.002250	.002250	.000930	.000930
	CaCl ₂	.000930	.000930	.000930	.000930
	NaH ₂ PO ₄	—	—	—	.000475
150	KH ₂ PO ₄	.000016	.000080	.000160	.001125
	Ca(NO ₃) ₂	.004500	.004500	.004500	.004500
	K ₂ SO ₄	.000225	.000190	.000110	—
	MgSO ₄	.002250	.002250	.002250	.002250
	NaH ₂ PO ₄	—	—	—	.000475
	NaNO ₃	—	—	—	.001710
	KNO ₃	.001710	.001710	.001710	—
250	KH ₂ PO ₄	.000016	.000080	.000160	.001125
	Ca(NO ₃) ₂	.004500	.004500	.004500	.004500
	MgSO ₄	.001125	.001125	.001125	.001125
	Mg(NO ₃) ₂	.001125	.001125	.001125	.001125
	NaH ₂ PO ₄	—	—	—	.000475
	NaNO ₃	.004380	.004510	.004670	.000475
	KNO ₃	.002220	.002090	.001930	—

* Trace elements supplied in the following forms: Mn, 0.25 ppm. (MnSO₄); B, 0.50 ppm. (H₂BO₃); Zn, 0.50 ppm. (ZnSO₄); Fe, 1.00 ppm. (FeSO₄).

Method of chemical analyses

Plant tissues were dried at 70°C. for 48 hours and ground in a semimicro Wiley mill to pass a 60-mesh screen. All tissues were redried overnight at 70°C. just prior to chemical analysis.

Total nitrogen was determined by the micro-Kjeldahl method. The rapid digestion method of Pepkowitz and Shive (16) was carried out with 35 per cent perchloric acid, and the distillation of ammonia, with the indicator suggested by Ma and Zuazaga (11).

The micromethod of the Association of Official Agricultural Chemists (1, pp. 133-134) was used for phosphorus analyses.

Total hydrolyzable carbohydrate determinations were made by hydrolyzing the plant tissue by boiling in 2.5 per cent HCl for 2½ hours. The content of reducing sugars was determined by the semimicro method of Wildman and Hansen (23).

Microscopic examinations were made for starch on cross sections of the stem close to the root. A solution of iodine in potassium iodide was used to stain the starch granules.

RESULTS

Plant growth

Within 4 days after nutrient treatments were begun, all seedlings receiving the lowest nitrogen supply (10 ppm.) showed definite signs of nitrogen deficiency. They were stunted and had thin, hard stems and small, pale yellowish green leaves. The undersides of the leaves had a purplish tinge (3, 7, 20). Seedlings grown with 50 and 100 ppm. nitrogen appeared considerably larger at all P levels than those grown at 10 ppm. and showed no signs of N deficiency. At higher nitrogen levels, seedling size appeared to be smaller than at 100 ppm. At the highest nitrogen levels the leaves were dark green, and the seedlings as a whole were soft and vegetative. These observations, together with data on green weight taken after 35 days of treatment (table 2), indicate that the optimum nitrogen level for maximum green weight production was 50 to 150 ppm.

Within 11 days after beginning of nutrient treatments, signs of phosphorus deficiency were apparent in seedlings receiving 0.5 ppm. phosphorus. These plants were small and similar in size to the low-nitrogen seedlings, with thin, short stems. Leaf coloring was bluish green instead of yellow, and the underside had a more pronounced purple tinge than did the low-nitrogen cultures as reported by others (3, 7, 20). Plant size appeared to increase at all nitrogen levels with each increase in phosphorus level up to 5 ppm., where the seedlings appeared largest of all in most cases. At 50 ppm. phosphorus the seedlings showed no increase in size over the next lower level at three out of the five nitrogen levels. Growth measurements taken at harvest also corroborated these observations made during the growth period with respect to the influence of phosphorus on plant size. These data (table 2) indicate that the optimum phosphorus level for maximum green weight production was at 5 ppm. in most cases.

Resistance to wilting

Representative plants from each nutrient treatment were graded on their ability to withstand wilting during a given period of exposure to conditions conducive to wilting. Seedlings grown at the lowest level of nitrogen and

phosphorus were affected least by exposure to the full noonday sun. At each phosphorus level, however, wilting tended to become more severe with increasing nitrogen; similarly, at each nitrogen level the degree of wilting increased as phosphorus concentration was increased in the substrate. Wilting was most severe in the high-nitrogen-high-phosphorous seedlings, which were also the softest, most vegetative plants. Part of the carbohydrate reserve of the low-nitrogen and low-phosphorus plants is transformed into mechanical tissues and thick cell walls, which retard the rate of water loss and cause the cells to

TABLE 2

Average green weights and stem heights of tops of tomato seedlings grown at varied N and P levels prior to storage and transplanting

NUTRIENT LEVELS		GREEN WEIGHT*	STEM HEIGHT*
N	P		
ppm.	ppm	gm	cm.
10	0.5	11.7	22.8
50	0.5	21.9	31.3
100	0.5	29.3	34.3
150	0.5	17.4	28.6
250	0.5	23.2	30.0
10	2.5	17.3	22.3
50	2.5	60.2	40.0
100	2.5	55.1	39.0
150	2.5	65.5	41.6
250	2.5	40.9	38.3
10	5.0	22.8	25.0
50	5.0	57.9	41.7
100	5.0	78.0	42.0
150	5.0	50.3	38.0
250	5.0	45.9	43.3
10	50.0	15.7	42.6
50	50.0	71.3	41.3
100	50.0	56.7	40.0
150	50.0	53.2	39.6
250	50.0	38.9	41.0

* Data are averages of two seedlings for each nutrient treatment.

become hard and less liable to collapse. This may partly account for a low degree of wilting in the low-nitrogen-low-phosphorus seedlings.

That the rate of water utilization in plants is influenced by internal factors has been pointed out by Nightingale (15). He observed that plants lacking an adequate supply of nitrogen tend to produce thick cell walls and mechanical fibers, schlerenchyma, and similar tissues. The effect of low nitrogen, therefore, is to produce a relatively xeromorphic plant. Shreve (19) also cited evidence of the influence of internal plant structure on the rate of water loss in stating that

the imbibitional attraction for water varies with composition of cell wall and protoplasm.

Behavior after transplanting

When the tomato seedlings were unpacked after the storage period, observations were made on general appearance and on root development. Seedlings from all treatments appeared to be severely wilted. New roots were found to be developing from the region of the first node of the stem as well as from the main

TABLE 3

Green weights and stem heights of individual stored tomato seedlings 10 days after being transplanted to uniform nutrient treatment

NUTRIENT LEVELS		GREEN WEIGHT	STEM HEIGHT
N	P		
<i>ppm.</i>	<i>ppm.</i>	<i>gm.</i>	<i>cm.</i>
10	0.5	41.0	43.0
50	0.5	58.0	51.0
100	0.5	72.0	48.0
150	0.5	45.0	50.0
250	0.5	44.0	45.0
10	2.5	45.0	42.0
50	2.5	91.0	53.0
100	2.5	104.0	54.0
150	2.5	71.0	56.0
250	2.5	82.0	54.0
10	5.0	24.0	39.0
50	5.0	128.0	53.0
100	5.0	80.0	52.0
150	5.0	47.0	54.0
250	5.0	57.0	54.0
10	50.0	40.0	40.0
50	50.0	82.0	59.0
100	50.0	82.0	53.0
150	50.0	70.0	57.0
250	50.0	51.0	56.0

root. At each phosphorus level, plants that had received the lowest nitrogen supply (10 ppm.) showed the best secondary root development, in both quantity and quality, during the storage period. Furthermore, at each nitrogen level, root quantity and quality declined with additional phosphorus in the differential treatments. Plants that had received the highest nitrogen and phosphorus concentrations showed no root development during this period. Rate of root development was correlated with nutrient conditions leading to high carbohydrate accumulation, as borne out by later analyses. Low-nitrogen and low-phosphorus plants were most capable of producing secondary roots during the storage period.

They also showed the greatest average increase in height of stems during storage.

The seedlings were then transplanted to their original pots and given the standard nutrient solution for 10 days. During this period, observations were made from time to time on the relative rates of recovery under good growth conditions. With respect to recovery from severe wilting, a similar pattern was followed as with relative resistance to wilting and with growth and development during storage. Plants that had originally been grown at the lowest phosphorus

TABLE 4

Ratios of green weights and stem heights 10 days after transplanting to weights and heights before storage

NUTRIENT LEVELS		WEIGHT RATIO	HEIGHT RATIO
N	P		
ppm.	ppm.		
10	0.5	3.50	1.89
50	0.5	2.65	1.63
100	0.5	2.46	1.40
150	0.5	2.59	1.75
250	0.5	1.90	1.50
10	2.5	2.65	1.88
50	2.5	1.50	1.33
100	2.5	1.89	1.38
150	2.5	1.09	1.36
250	2.5	2.00	1.41
10	5.0	1.04	1.56
50	5.0	2.21	1.27
100	5.0	1.03	1.24
150	5.0	—	1.42
250	5.0	1.24	1.25
10	50.0	2.50	—
50	50.0	1.15	1.43
100	50.0	1.44	1.32
150	50.0	1.32	1.44
250	50.0	1.31	1.36

and nitrogen levels were the first to resume turgidity under uniform nutrient conditions. As the original nitrogen level was increased, the time required for the transplants to resume turgidity was also increased; at the highest nitrogen levels, the plants remained wilted for a considerable time. Increasing phosphorus levels had the same effect on time of recovery from wilting as did increasing nitrogen levels.

Green weight and stem height of tops were measured after the 10-day treatment with standard solution. On the basis of green weight, plants that had originally received the second lowest phosphorus supply (2.5 ppm.) produced

the greatest amount of growth at most of the nitrogen levels, as shown in table 3. Weights generally decreased with increase in phosphorus from this point. Green weights were lowest, however, in the phosphorus-deficient plants (0.5 ppm. P) with one exception. There were no great differences in stem heights of plants grown with various phosphorus levels at any nitrogen level. With respect to nitrogen levels, the heaviest plants were those produced originally at the 50 ppm. and 100 ppm. concentrations at each different phosphorus level. There were no great differences in stem heights at the different phosphorus levels with nitrogen levels between 50 and 250 ppm.

Data on green weight were compared with similar measurements taken at the first harvest before the seedlings were stored. Growth resumption, as indicated by the ratio of the final weight to be initial weight (table 4), was greatest in the plants that had been grown with least phosphorus (0.5 ppm. P). Similar results were observed with respect to variations in original nitrogen concentrations; the lowest-nitrogen plants (10 ppm.), with one exception, showed the fastest growth rate after being supplied with complete nutrient solution. The ratio of final to initial stem height was also calculated (table 4). As with weight increases the greatest increases in height during the recovery period occurred with the plants originally low either in phosphorus or in nitrogen. Rate of renewal of root development after transplanting was also considered as a criterion of growth resumption of the plants. The most extensive root systems were displayed by the same plants that showed superiority in weight and height during this period, the optimum nitrogen level being 50 ppm. and the optimum phosphorus level, 2.5 ppm. Though the plants at the lowest nitrogen and phosphorus levels showed the greatest average increase in rate of growth after transplanting, *the plants grown at the 2.5 ppm. phosphorus concentration and the 50-100 ppm. nitrogen levels were judged to be in the best condition for potential crop production after transplanting to standard conditions.*

Chemical analyses

The results of quantitative chemical analyses for total nitrogen, phosphorus, and carbohydrate content of tomato plants prior to and 10 days after transplanting are presented in tables 5 and 6 respectively.

Nitrogen. Nitrogen contents of the seedlings were found to be higher with increased concentrations of nitrogen in the culture solutions at any given phosphorus level up to a certain point (table 5). The increases were greatest from 10 to 50 ppm. and from 50 to 100 ppm. nitrogen levels. Beyond the concentration which proved optimum for plant growth (100 ppm.), the increase in nitrogen content did not correspond with the increase in nitrogen supply.

Nitrogen contents at the lowest phosphorus concentration (0.5 ppm.) were little different from those at the next higher concentration (2.5 ppm). From this point on, nitrogen content generally increased with increase in phosphorus concentration. Bartholomew *et al.* (2) presented evidence that a lack of phosphorus may increase nitrogen absorption.

In comparison with the data in table 5, analyses made on transplants (table 6)

showed that seedlings which had originally received the lowest nitrogen and lowest phosphorus supplies had apparently absorbed nitrogen at more rapid rates after being transplanted to standard nutrient conditions than did plants grown at the higher nitrogen and phosphorus levels. *This is correlated with the capacity of low-phosphorus plants to increase in height and weight as well as with their resistance to wilting and subsequent recovery from excessive water loss after transplanting.*

TABLE 5

Total nitrogen, phosphorus, and carbohydrate contents of tops of tomato seedlings grown at varied N and P levels prior to storage and transplanting

NUTRIENT LEVEL		N CONTENT	P CONTENT	CARBOHYDRATE CONTENT
N	P			
ppm	ppm.	per cent*	per cent*	per cent*
10	0.5	2.13	.254	38.0
50	0.5	3.22	.107	29.1
100	0.5	3.73	.217	22.6
150	0.5	3.61	.370	19.9
250	0.5	3.70	.203	21.0
10	2.5	2.19	.368	35.3
50	2.5	2.76	.250	22.5
100	2.5	3.53	.231	19.1
150	2.5	3.80	.346	16.9
250	2.5	3.80	.231	18.8
10	5.0	2.23	.520	32.6
50	5.0	2.75	.376	24.6
100	5.0	3.61	.242	17.8
150	5.0	4.04	.392	16.1
250	5.0	4.02	.334	16.0
10	50.0	2.21	.686	33.5
50	50.0	2.98	.631	24.4
100	50.0	3.32	.532	18.5
150	50.0	3.99	.730	14.5
250	50.0	4.28	.950	16.0

* Of dry matter.

Phosphorus. With one exception, the phosphorus content of plants in all treatments was found to increase regularly with increase in phosphorus supply (table 5). With regard to variations in substrate nitrogen, however, the highest phosphorus contents were found, in general, at the lowest nitrogen level. Phosphorus absorption, then, appeared to decrease with increased nitrogen until the optimum nitrogen range (50–100 ppm.) was reached, where it was lowest in most cases. Beyond this point, phosphorus accumulation increased with further increase in nitrogen concentration.

Like nitrogen, phosphorus was apparently accumulated most rapidly by low-

nitrogen and low-phosphorus plants during the period of recovery after transplanting, as brought out by comparison of phosphorus contents of plants in corresponding treatments (tables 6 and 5).

Carbohydrates. The total hydrolyzable carbohydrate content of plants before transplanting was found to be highest at the lowest nitrogen level (table 5). At each phosphorus concentration, the carbohydrate content decreased with increase in available nitrogen until the highest nitrogen level (250 ppm.) where it

TABLE 6

Total nitrogen, phosphorus, and carbohydrate contents of tops of tomato seedlings 10 days after transplanting to uniform nutrient treatment

NUTRIENT LEVELS		N CONTENT	P CONTENT	CARBOHYDRATE CONTENT
N	P			
ppm.	ppm.	per cent*	per cent*	per cent*
10	0.5	3.33	0.541	16.9
50	0.5	3.82	0.515	12.5
100	0.5	3.73	0.400	14.5
150	0.5	3.82	0.431	10.6
250	0.5	4.52	0.541	20.8
10	2.5	3.40	0.564	14.8
50	2.5	2.79	0.334	21.7
100	2.5	3.49	0.326	16.3
150	2.5	3.30	0.295	22.0
250	2.5	3.44	0.400	18.1
10	5.0	3.58	0.699	13.3
50	5.0	3.03	0.513	19.0
100	5.0	3.99	0.405	17.3
150	5.0	5.05	0.408	16.5
250	5.0	4.51	0.498	13.5
10	50.0	3.11	1.030	17.5
50	50.0	3.01	0.662	18.8
100	50.0	3.73	0.515	17.0
150	50.0	3.99	0.704	20.8
250	50.0	4.62	0.714	15.8

* Of dry matter.

increased slightly in most cases. Similarly, there was a tendency for carbohydrate content to decrease with increased phosphorus supply at the respective nitrogen levels, though the decrease was not so great with phosphorus increments as with additional nitrogen. These results were in agreement with reported results of Hartwell (6), Kraus and Kraybill (9), and others (4, 8, 12, 14, 21). The carbohydrate contents of the tops of the seedlings 10 days after transplanting to a uniform nutrient treatment are presented in table 6. In most cases these carbohydrate contents were less than those of comparable seedlings before transplanting. Furthermore, the depletion of carbohydrate reserves was more pro-

nounced in the plants originally grown at the lower than at the higher nutrient levels of nitrogen and phosphorus.

Starch. Though starch was not determined quantitatively, microscopic examination of cross sections of stems cut at a point about 5 cm. from the root showed the same trends as did total carbohydrate analyses. Stems of plants grown with lowest nitrogen supplies showed an abundance of starch granules, particularly in the endodermis and in the pith next to the vascular tissue. As the nitrogen level increased, the amount of starch in the endodermis and pith appeared to decrease at all phosphorus levels. The lowest phosphorus levels in each nitrogen range contained the greatest abundance of starch granules. At the highest nitrogen and phosphorus levels no starch could be discerned.

SEASONAL EFFECTS

A second series of tomato seedlings was grown the following fall season from October to December in exactly the same manner as the first series. Because of the difference in climatic factors accompanying the first and second series, certain significant differences occurred in the responses of the plants to nutrient treatments.

In general, growth of the plants was somewhat slower in the second series than in the first series, presumably because of the lower light conditions under which the seedlings were grown. The same trends in response to differential nutritional treatments were observed as with the first series. Again there was a definite correlation between the type of growth exhibited by the seedlings before transplanting and the concentration of nitrogen and phosphorus supplied them in the nutrient medium, the optimum levels being at 100 ppm. nitrogen and 5 ppm. phosphorus. When the seedlings were pulled and exposed to the bright sun's rays, those which had received high nitrogen and phosphorus supplies were again least resistant to wilting. After being transplanted to their original pots following the storage period and after being supplied with uniform nutrient treatment, the low-nitrogen and low-phosphorus plants "picked up" most rapidly, and the high-nitrogen and high-phosphorus cultures were again the slowest to recover from wilting. In this series, however, the greatest average weights and stem heights after transplanting, occurred with plants originally grown at 0.5 ppm. phosphorus, whereas in the preceding series the average weights of the seedlings were generally superior at 2.5 ppm. P to those at other phosphorus levels. The optimum nitrogen level for renewed growth was at 100 ppm., as in the first series.

The nitrogen and phosphorus contents of the seedlings in this second series were decidedly higher than in the summer-grown seedlings in corresponding nutrient treatments. As in the first series, the total hydrolyzable carbohydrate contents were highest at the lowest nitrogen level. There was a general tendency for carbohydrate content to decrease with increase in available nitrogen and phosphorus, though not so abruptly as in the summer series. As was expected from the general behavior of seedlings in the summer and fall series, the total carbohydrate content tended to be lower in the fall series than in the correspond-

ing plants grown under summer conditions of greater available light. Microscopic examination of stems showed this fact to be true also of starch accumulation.

DISCUSSION

The second series, in general, served to corroborate the evidence presented in the first experiment that the relative phosphorus and nitrogen nutrient levels are related to carbohydrate content, and that higher carbohydrate content is associated with the ability of tomato seedlings to withstand adverse handling conditions and rapidly to resume normal growth when transplanted to normal nutrient conditions. In addition, this series emphasized the fact that the relative carbohydrate content required for resumption of growth of transplanted tomato seedlings varies with seasonal climatic conditions, being somewhat lower in fall.

The discrepancies which were found to exist between the first and second series with respect to the phosphorus level most conducive to rapid plant growth resumption may be attributed to seasonal influences upon plant growth in general. During the fall season a reduction in available light resulted in a "less nitrogen- or phosphorus-starved" type of plant associated with an increase in both nitrogen and phosphorus within the plant and a decrease in carbohydrate percentage as compared with plants grown during the summer (17). The fall-grown series, therefore, appeared to be less deficient in nitrogen and phosphorus than was the summer series at the identical low concentrations of these elements in the cultural solutions. In other words, the phosphorus level in the second series grown in fall (0.5 ppm.) corresponded with the second lowest level in the summer series (2.5 ppm.). In the summer-grown seedlings at the phosphorus-deficiency level of 0.5 ppm. much of the carbohydrate reserve was converted to rigid tissue structures, thus impeding cell expansion and rapid renewal of growth. In the fall series, carbohydrate accumulation was not so high at this same low phosphorus level, resulting in formation of less mechanical tissue to impede cell expansion and yet providing an adequate amount of energy-yielding carbohydrate reserves to initiate normal growth.

The importance of an available carbohydrate supply in the resumption of growth of tomato seedlings has been emphasized by Went and Carter (22), who showed that sugar-solution sprays applied to the leaves before transplanting prevented the severe setback ordinarily experienced by untreated tomato seedlings when transplanted.

SUMMARY AND CONCLUSIONS

Marglobe tomato seedlings were grown at different nitrogen and phosphorus levels in an attempt to correlate the carbohydrate reserve accumulated in the plants at each nutritional level with observed responses of the plants to severe handling treatment prior to transplanting.

Plant size increased with increase in available nitrogen and phosphorus to a given level, beyond which an increased supply of either nutrient element was unaccompanied by further increase in growth. The optimum nutrient level for

total growth before transplanting was at 100 ppm. nitrogen and at 5 ppm. phosphorus.

Plants that had received a moderate nitrogen supply (100 ppm.) and a low but not seriously deficient phosphorus supply (2.5 ppm.) were best able to initiate and continue good growth on the basis of green weight, secondary root production, and increase in stem height when transplanted to standard nutrient after exposure to severe wilting conditions.

The phosphorus and nitrogen nutrient concentrations that proved optimum for initiation and continuation of growth of the seedlings transplanted to standard nutrient treatment after being subjected to severe conditions of wilting and to storage were associated with the relative carbohydrate contents of the plant tissues.

It is concluded, therefore, that although an inadequacy in the nutrient supply of both nitrogen and phosphorus may cause accumulation of a carbohydrate reserve in the tomato plant, it appears advisable from the standpoint of producing seedlings of the best quality for successful transplanting, that this carbohydrate reserve be brought about by a limitation of phosphorus rather than of nitrogen in the nutrient supply.

REFERENCES

- (1) Association of Official Agricultural Chemists 1940 Official and Tentative Methods of Analysis, ed. 5. Washington, D.C.
- (2) BARTHOLOMEW, R. P., WATTS, V. M., AND JANSSEN, G. 1933 Effect of variations in nutrient media upon nitrogen, phosphorus, and potassium content of plants with special reference to the tomato. *Ark. Agr. Exp. Sta. Bul.* 288.
- (3) ECKERSON, S. H. 1931 Influence of phosphorus deficiency on metabolism of the tomato. *Boyce Thompson Inst. Contrib.* 3: 197-217.
- (4) FOSTER, A. C., AND TATMAN, E. C. 1938 Influence of certain environmental conditions on congestion of starch in tomato stems. *Jour. Agr. Res.* 56: 869-888.
- (5) Georgia Coastal Plain Experiment Station 1941 Suggestions for commercial production of tomatoes in southern Georgia for sale in the eastern and midwestern states. Mimeo Paper 3
- (6) HARTWELL, B. L. 1916 Starch congestion accompanying certain factors which retard plant growth. *R. I. Agr. Exp. Sta. Bul.* 165.
- (7) HEPLER, J. R., AND KRAYBILL, H. R. 1925 Effect of phosphorus upon the yield and time of maturity of the tomato. *N.H. Agr. Exp. Sta. Tech. Bul.* 28.
- (8) JANSSEN, G., BARTHOLOMEW, R. P., AND WATTS, V. M. 1934 Some effects of N, P, K, on composition and growth of tomato plants. *Ark. Agr. Exp. Sta. Bul.* 310
- (9) KRAUS, E. J., AND KRAYBILL, H. R. 1918 Vegetation and reproduction with special reference to the tomato. *Oreg. Agr. Exp. Sta. Bul.* 149: 1-90.
- (10) KRAYBILL, H. R. 1930 Plant metabolism studies as an aid in determining fertilizer requirements. *Indus. and Engin. Chem., Analyt. Ed.* 22: 275-276.
- (11) MA, T. S., and ZUAZAGA, G. 1942 Micro-Kjeldahl determination of nitrogen. A new indicator and an improved method. *Indus. and Engin. Chem., Analyt. Ed.* 14: 280-281.
- (12) MACGILLIVRAY, J. H. 1927 Effect of phosphorus on composition of tomato plant. *Jour. Agr. Res.* 34: 97-126.
- (13) MANNS, T. F. 1929 Tomato seed bed studies. *Del. Agr. Exp. Sta. Bul.* 162.
- (14) NIGHTINGALE, G. T., ET AL. 1931 Effect of calcium deficiency on nitrate absorption and on metabolism in the tomato. *Plant Physiol.* 6: 605-630.

- (15) NIGHTINGALE, G. T. 1937 Nitrogen nutrition of green plants. *Bot. Rev.* 3: 85-174.
- (16) PEPKOWITZ, L. P., AND SHIVE, J. W. 1942 Kjeldahl nitrogen determination. A rapid wet-digestion micromethod. *Indus. and Engin. Chem., Analyst. Ed.* 14: 914-916.
- (17) REED, H. S. 1907 Value of certain nutritive elements to the plant cell. *Ann. Bot.* 21: 501-543.
- (18) SHIVE, J. W., AND STAHL, A. L. 1927 Constant rates of continuous solution renewal for plants in water cultures. *Bot. Gaz.* 84: 317-323.
- (19) SHREVE, E. B. 1916 An analysis of the causes of variations in the transpiring power of cacti. *Physiol. Rev.* 2: 73-127.
- (20) WALLACE, T. 1943 Diagnosis of Mineral Deficiencies in Plants. H. M. Stationery Office, London.
- (21) WATTS, V. M. 1931 Some factors which influence growth and fruiting of the tomato. *Ark. Agr. Exp. Sta. Bul.* 267.
- (22) WENT, F. W., AND CARTER, M. 1948 Growth response of tomato plants to applied sucrose. *Amer. Jour. Bot.* 35: 95-105.
- (23) WILDMAN, S. G., AND HANSEN, E. 1940 A semi-micromethod for the determination of reducing sugars. *Plant Physiol.* 15: 719-725.

FAILURE OF THE INTERNATIONAL SODA METHOD IN ESTIMATING CLAY IN A SUBSOIL, AS REVEALED BY THE BASE-EXCHANGE CAPACITY

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Since discovery of the phenomenon of base-exchange by Thompson (8) and Way (10), all investigations on the subject have led to the view that this phenomenon in soil is due not to the entire soil, but chiefly to the colloidal fraction, though the silt fractions of some soil types have been found to exhibit feeble base-exchange properties. Hissink (1), for example, found that, for some soil types, 90 to 95 per cent of the base-exchange capacity is due to particles belonging to the clay fraction.

In a detailed study of the physicochemical properties and mechanical composition of a number of soil profile samples collected from different parts of India, a subsoil from Nagpur was found to have the following properties: organic matter, 0.02 per cent; clay, 6.3 per cent; silt, 5.8 per cent; base-exchange capacity per 100 gm. of air-dry soil, 62 me.

From these data it is obvious that if the clay fraction is regarded as the seat of base exchange, the sample would have an exchange capacity of about 1,000 me. per 100 gm. of clay, and even if both silt and clay are regarded as the seat of the exchange reaction, this would amount to 500 me. per 100 gm. of clay plus silt. As no minerals with so high an exchange capacity have yet been found, this soil may be regarded as peculiar in its base-exchange capacity. The object of the present investigation was to determine the reason for this peculiar behavior.

One or more of the following factors might be responsible:

1. A new clay mineral.
2. Some rock minerals with high exchange capacity in the coarser fractions of the soil.
3. Incomplete dispersion of the clay.
4. Partly weathered products showing base-exchange phenomena but not sufficiently weathered to exhibit all the properties of secondary minerals.

EXPERIMENTAL METHODS

Mechanical analysis of 100 gm. of the sample was made by the international soda method (2, 5), clay, silt, and sand fractions being separated in five 20-gm. aliquots. The base-exchange capacity of each of these fractions was determined by the Ba-acetate- NH_4Cl method of Parker (3).

Subsequently, one lot of the sample was subjected to Truog's treatment (9); one to Tamm's treatment (7); one to an acid treatment, in which H_2O_2 was first added to remove organic matter, then the sample was leached with 0.5 *N* acetic

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acid until the exchangeable bases were completely removed, and finally the sample was washed with distilled water; and one lot was untreated. Mechanical analyses of these four lots were carried out as follows: 20-gm. samples were placed in 600-ml. beakers and treated with 6 per cent H_2O_2 until further addition produced no effervescence. Next, N HCl was added in sufficient quantity to bring the acidity of the total solution to $0.2 N$. The suspension was filtered, washed, and transferred to a bottle after the volume was made up to 2 liters by addition of 15 ml. N NaOH . The suspension was shaken on a rotary shaker for 8 hours. Next day the clay and silt samples were taken by the pipette method, and the pH of the suspension was estimated with a hydrogen electrode. A further quantity of N NaOH was added, shaken thoroughly, and clay and silt samples were taken as usual. The process was continued till a constant value for clay and silt was obtained or until the suspension was flocculated on addition of NaOH .

TABLE 1
Base-exchange capacity of different fractions

	AIR-DRY BASIS	OVEN-DRY BASIS
	me.	me
Clay	76.9	94.2
Silt	62.0	71.6
Fine sand	60.4	69.0
Coarse sand	53.0	60.0
Soil	62.0	72.0
Soil (H_2O_2 -treated and acid-leached)	58.5	68.0

RESULTS

Results of the mechanical analysis by the international soda method were as follows (air-dry basis): clay, 13.5 per cent; silt, 6.7 per cent; fine sand, 15.0 per cent; coarse sand, 63.0 per cent. The base-exchange capacities of these fractions are given in table 1.

From table 1 it is obvious that the clay shows no abnormal behavior, nor does it indicate the presence of any unknown mineral of high base-exchange capacity; but fractions other than the clay show a very high base-exchange capacity. The coarse sand fraction, for example, shows 53.0 me. per 100 gm. (air-dry basis); that is, the capacity is roughly 70 per cent that of the clay.

The clay was found to have the following chemical composition: SiO_2 , 63.1 per cent; Al_2O_3 , 12.2 per cent; Fe_2O_3 , 15.2 per cent; MgO , 7.0 per cent; adsorbed water, 22.5 per cent; combined water, 6.8 per cent. These data, specially those of adsorbed and combined water, indicate that the clay possibly belongs to the montmorillonite group. This was further corroborated by its dehydration curve, which was found to be similar to that of the montmorillonitic mineral.

To test the second probable reason for the peculiar behavior, the base-exchange capacities of a number of rock minerals likely to be present in this soil, the parent material of which is a basalt, were determined. The minerals, from Indian

sources, were first powdered and passed through a 1-mm. sieve. The results—hornblende, 0.6 me.; feldspar, 0.76 me.; pyroxene (augite), 1.6 me.; talc, 0.2 me.; basalt, 0.25 me.; and actinolite, 0 me. per 100 gm.—showed that the primary rock minerals studied had virtually no base-exchange capacity, and therefore the high capacity exhibited by the coarser fractions was not due to primary minerals.

Of the two remaining possibilities, incomplete dispersion might be due to one or more of the following factors:

1. Cementation due to organic matter.
2. Cementation due to calcium carbonate.
3. Cementation due to calcium sulfate.
4. Cementation due to free sesquioxides.
5. Addition of insufficient alkali during dispersions.
6. Incomplete removal of exchangeable bases present in the soil.

The first three factors could not be responsible, however, since the soil was found to contain only 0.02 per cent organic matter, 0.026 per cent carbonate, and no CaSO_4 . Furthermore, pretreatment of the soil with 6 per cent H_2O_2 and 0.2 *N* HCl before separation of the different fractions would eliminate any possibility of cementation due to organic matter, lime, or calcium sulfate.

Results of the analyses, shown in table 2, of the four lots of soil—Truog-treated, Tamm-treated, acid-treated, and untreated—might provide some clue to the relation of the remaining factors to incomplete dispersion. These results may be summarized as follows:

1. The pH of the suspension was different for differently treated lots of soil with the same amount of alkali.
2. With 15 ml. of alkali:
 - (a) The untreated soil had the highest pH (11.0); the acid-treated and the Tamm-treated soil had a pH of only 9.9.
 - (b) The percentage of silt showed only a slight variation for all the treatments (11.9–14.3 per cent).
 - (c) The percentage of clay varied from 17.4 to 36.1 in the different treatments, the order being Tamm-treated > acid-treated > Truog-treated > untreated.
3. With further additions of alkali, the amount of clay increased in all lots of soil, the order, however, remaining the same until a total of 24 ml. of alkali was added, when the order became acid-treated > Tamm-treated > Truog-treated > untreated.
4. The amount of silt remained virtually constant for the differently treated lots of soil with increasing amounts of alkali.
5. For the Truog-treated soil the pH of the suspension with 15 ml. of alkali was 10.5, which was raised to 11.8 by addition of 34 ml. of alkali. The highest figure for clay was obtained with 29 ml. of alkali, the corresponding pH being about 11.7.
6. For the Tamm-treated soil the pH of the suspension rose to 11.7 with 34 ml. of alkali. The highest figure for clay was obtained with 24 ml. of alkali, the corresponding pH being about 11.4.
7. For the acid-treated soil the pH of the suspension increased to 11.7 with 34 ml. of alkali. The highest figure for clay, 45.5 per cent, was obtained with 29 ml. of alkali, the corresponding pH being 11.6.
8. For the untreated soil, the pH of the suspension rose to 11.8 with 34 ml. alkali. The highest amount of clay, 28.2 per cent, was obtained with 26.5 ml. of alkali, the corresponding pH being about 11.6.

TABLE 2
Mechanical analyses of differently treated lots of soil

SOIL TREATMENT	ALKALI ADDED	pH	CLAY AND SILT	CLAY	SILT
	<i>ml.</i>		<i>per cent</i>	<i>per cent</i>	<i>per cent</i>
Truog	15	10.5	37.2	24.8	12.4
	17	10.7	41.6	28.5	13.1
	19	11.1	42.7	29.6	13.1
	21.5	11.3	42.7	30.3	12.4
	24	11.4	42.0	29.5	12.5
	29	—	43.5	31.4	12.1
	34	11.8	43.2	Flocculation occurs	
Tamm	15	9.9	48.2	36.1	12.1
	17	10.6	51.3	39.5	11.8
	19	11.0	52.5	40.4	12.1
	21.5	11.2	53.1	40.6	12.5
	24	11.4	52.8	41.2	11.6
	26.5	—	50.6	40.0	10.6
	29	—	54.2	Flocculation occurs	
Acid	15	9.9	41.0	26.7	14.3
	17	10.6	44.5	30.3	14.2
	19	11.0	49.3	34.2	15.1
	21.5	11.2	52.2	38.2	14.0
	24	11.4	55.0	41.4	13.6
	26.5	—	55.8	42.5	13.3
	29	—	58.6	45.5	13.1
Untreated	34	11.7	57.9	—	—
	15	11.0	29.3	17.4	11.9
	17	11.0	34.5	22.2	12.3
	19	11.2	35.8	23.8	12.0
	21.5	11.3	35.9	24.4	11.5
	24	11.5	38.0	25.2	12.8
	26.5	—	39.5	28.2	11.3
	29	—	40.1	25.7	11.4
	34	11.8	40.0	Flocculation occurs	

DISCUSSION

Before the behavior of the differently treated lots of soil toward mechanical analysis is discussed, it might be well to review certain effects of the treatments, which are assumed to be as follows:

1. In Truog's treatment, some of the original exchangeable bases of the soil may remain unaffected and some sodium may enter into the complex, inasmuch as the reagents used include sodium sulfide, oxalic acid, and sodium chloride, and the pH of the medium is never below 3.5.
2. In Tamm's treatment, most of the original exchangeable bases will be removed, and the complex may be saturated to some degree with ammonium ions, as the reagents used are oxalic acid and ammonium oxalate, and the pH is too low.

3. In the acid-treated soil, all the original exchangeable bases have been removed.
4. In the untreated soil, all the exchangeable bases remain.
5. Treatment with hydrochloric acid during mechanical analysis has not been able to remove all the exchangeable bases.

On the basis of these assumptions, the behavior of the soils may be thus explained. The high pH of the untreated soil with 15 ml. of *N* alkali in comparison with that of any of the treated soils may be due to the presence of divalent exchangeable bases. The amount of these divalent bases together with the alkali added would be greater for the untreated soil than for any of the other soils. The untreated soil also showed the lowest content of clay. Since the divalent bases, instead of dispersing clay, tend to form aggregates, low figures for clay would be expected.

That the Tamm-treated soil with 15 ml. of *N* alkali gave a higher figure for clay than did any of the other lots of soil was due to the presence of NH_4 ions as exchangeable bases, the NH_4 ions being a good dispersing agent, though not equivalent to Na ions. That the acid-treated soil ultimately gave the highest figure for clay was probably due to complete absence of any other bases than Na,

TABLE 3
Mechanical analysis of soil under different treatments

SOIL TREATMENT	COARSE SAND	FINE SAND	SILT	CLAY
	<i>per cent</i>	<i>per cent</i>	<i>per cent</i>	<i>per cent</i>
Truog	22.1	10.1	12.1	32.7
Tamm	14.2	13.5	11.6	42.8
Acid	11.7	7.6	13.1	46.6
Untreated	23.0	11.6	11.3	29.2

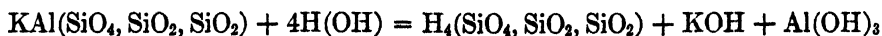
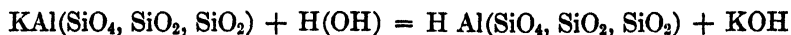
whereas the Tamm-treated soil contained, other than Na, a small quantity of bases that may have a coagulating tendency at a higher pH.

Incidentally, since the results showed that the clay in this Nagpur subsoil was not completely dispersed at pH 10.5, the observations of Sen *et al.* (6) and of Puri (4), that maximum dispersion takes place at pH 10.5 for all soils, require modification.

Final results for mechanical analysis of the soil under different treatments are given in table 3. The maximum amount of clay, 46.6 per cent, was found in the acid-treated soil. This amount of clay cannot account for the entire exchange capacity of the soil, since that of clay is 94.2 me. per 100 gm., or roughly only about 43.9 me. for 46.6 gm. It follows, then, that the coarser fractions also contribute to the exchange capacity of the soil.

It has been shown that the rock minerals which are likely to be present in basalt do not exhibit appreciable base-exchange properties. But the rock minerals as they exist in the soil under investigation may be partly weathered, and the base-exchange capacity may be due to the presence of these partly weathered materials. According to Wiegner (11), the first stage in the weathering of silicate minerals is a hydrolysis and base exchange: the hydrogen ion from water is ex-

changed with the cation of the minerals. He has written the equations for decomposition as follows:



He holds that "the entry of the hydrogen from water into the molecule of the silicate, replacing the potassium of the feldspar, may possibly occur with the lattice structure still intact, but the degree of dispersion in the interior will already have been altered. The entry of the small hydrogen ion in place of the large potassium atom makes the crystal more open, holes and capillaries arise and it is possible that the ionic-exchange processes can occur as they do in zeolites."

Next in order was to find out whether the base-exchange material could be removed from the coarser fractions. The Tamm-treated sand was treated with NaOH and the suspension decanted off. Finally the fraction was heated with water, and it was then observed that fine particles were continually coming into suspension. On repeated heating of the fraction with water and subsequent decantation of the suspension, a large quantity of fine particles was separated from the coarser fraction. This separation went on almost indefinitely as the process was repeated. The process of repeated heating could not be continued long, however, and complete separation of fine particles from the coarser fraction could not be effected because of abnormal bumping in the later stages.

The base-exchange capacity of the residue from the foregoing treatment was found to be reduced from 53.0 me. to 7.1 me. per 100 gm. (air-dry basis). It is believed that if the process could have been continued, all the base-exchange material could have been removed.

CONCLUSION

The peculiar behavior of the soil under investigation, a subsoil from Nagpur, was definitely proved to be due in some degree to incomplete dispersion of the clay during mechanical analysis by the international soda method, resulting in a low figure for clay, and in some degree to the presence of partly weathered material in the coarser fractions.

REFERENCES

- (1) HISSINK, D. J., ET AL. 1935 A study of absorption complex for certain soils. *Trans. 3rd Internatl. Cong. Soil Sci.* 1: 82-84.
- (2) International Society of Soil Science 1934 Dispersion of soil and grouping of fractions in mechanical analysis. *Trans. First Conn.* 1934: 303-305.
- (3) PARKER, H. J. 1929 The determination of exchangeable hydrogen in soils. *Jour. Amer. Soc. Agron.* 21: 1030-1039.
- (4) PURI, A. N. 1936 Dispersion for mechanical analysis. *Soil Sci.* 42: 267-272.
- (5) ROBINSON, G. W. 1933 The dispersion of soils for mechanical analysis. Imp. Bur. Soil Sci. Tech. Commun. 26.
- (6) SEN, A. T., ET AL. 1932 Mechanical analysis of laterite soils. *Indian Jour. Agr. Sci.* 2: 516-524.

- (7) TAMM, O. 1934 Imp. Bur. Soil. Sci. Mo. Letter 34.
- (8) THOMPSON, H. S. 1850 On the absorbent power of soils. *Jour. Roy. Agr. Soc.* 11: 68-74.
- (9) TRUOG, E., ET AL. 1937 Procedure for special type of mechanical and mineralogical soil analysis. *Soil Sci. Amer. Proc.* (1936) 1; 101-112.
- (10) WAY, J. T. 1850 On the power of soils to absorb manure. *Jour. Roy. Agr. Soc.* 11: 313-379.
- (11) WIEGNER, G. 1931 Some physicochemical properties of clays. *Jour. Soc. Chem. Indus.* 50: 65T-71T.

PROFILE STUDIES OF NORMAL SOILS OF NEW YORK: I. SOIL PROFILE SEQUENCES INVOLVING BROWN FOREST, GRAY-BROWN PODZOLIC, AND BROWN PODZOLIC SOILS

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This is the first of a series of articles dealing with the properties and inter-relationships of the well-drained soils on the gently rolling uplands in New York. This article is presented (a) to describe the morphology and geography of these "normal" soils as background information for more detailed physical and chemical studies to follow, and (b) to present a working hypothesis that, on calcareous materials in New York, soil development may proceed through a series of "normal profiles" from brown forest through gray-brown podzolic to brown podzolic soils or podzols.

MORPHOLOGY OF NORMAL SOILS

Four kinds of profiles occur in well-drained positions on the gently rolling uplands of New York. These are classified as members of the brown forest, gray-brown podzolic, brown podzolic, and podzol great soil groups.

The brown forest soils are intrazonal calcimorphic soils of the humid region. They occur in New York only in limited areas in region 2 (fig. 1) and are confined to strongly calcareous parent materials. The profile is characterized by a neutral solum, a thick very dark brown granular A₁ horizon, and a brown B horizon that is transitional to the parent material. There is little or no illuvial concentration of silicate clays or sesquioxides in any horizon. The modal properties of the group are probably best expressed in New York in Grenville loam, a description of which follows:²

A₀₀—0 to 1 inch thick

Leaf litter of deciduous trees. This is almost completely decomposed by midsummer and incorporated with mineral soil. Biological activity is very high.

A₁₁—0 to 7 inches

Very dark brown (10 YR 2/2) loam with strongly developed medium granular structure. The horizon is very friable, neutral, high in organic matter, and filled with roots. Numerous worm casts are present. This horizon grades throughout the lower 2 inches into:

A₁₂—7 to 12 inches.

Dark brown (10 YR 4/3) loam with moderately developed medium crumb structure. This horizon is also very friable and neutral. It is a transitional horizon, lower in organic

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² Munsell color notations for the moist soil are used. Terms for soil structure are those defined in the mimeographed report of the Committee on Soil Structure and Consistence, by the Correlation Staff of the Soil Survey Division, U. S. Department of Agriculture, dated March 29, 1944.

matter than horizon A₁₁. Numerous worm casts are present. Roots are numerous. The horizon grades throughout its thickness to:

B—12 to 18 inches

Brown (7.5 YR 4/4) loam with weakly developed fine nuciform or coarse crumb structure. This horizon is also very friable and neutral. Organic matter occurs in worm casts, and roots are numerous. There is no evidence of clay accumulation from horizons above. Chroma decreases with depth.

C—18 inches plus

Grayish brown (2.5 YR 4/2) loam or fine sandy loam firm glacial till. The till has a weakly thin platy to weakly fine blocky structure and is moderately firm in place. It is strongly calcareous. Roots penetrate the horizon and a few worm casts occur in the upper part. A transitional horizon may be present in the topmost 6 inches.

The Grenville series was examined in 1948 by Dr. Erwin Frei of Zurich, Switzerland, and was considered by him to be typical of one segment of the *Braunerde* of Switzerland, which includes also some soils we would class as gray-brown podzolic (11).

The gray-brown podzolic soils are considered zonal soils of humid temperate regions. In New York, they occur generally throughout region 2 (fig. 1) and in smaller areas in some parts of region 1. They, like the brown forest soils, are invariably derived from calcareous parent materials in all of New York except possibly the southern part of the Hudson Valley and Long Island, but they are characterized by a distinct A, B, C profile in which the A horizon is clearly eluviated and the B horizon contains more clay than either the A or the C. The solum is generally thicker than that of the brown forest soils on similar materials, and the A₁ horizon is thinner. The soils in New York have the essential features of the gray-brown podzolic soils as described by Baldwin (1).

The modal gray-brown podzolic profile in New York differs from that of the Miami series as described by Brown and Thorp (2) mainly in having two subdivisions of the A₂ horizon. In almost all places, there is an upper yellowish brown A₂₁ horizon, which is lacking in soils of the gray-brown podzolic group farther south. In the most acid members of the gray-brown podzolic group in New York, this horizon has color, structure, and consistence very much like those of the B₂₁ horizon of weakly developed brown podzolic soils. Its thickness varies directly with acidity; it may be very thin and almost completely masked by organic matter from the A₁ horizon in some nearly neutral soils; it may be as much as 18 inches thick in other more strongly acid soils. The underlying A₂₂ horizon is pale brown or grayish brown and is essentially similar to the A₂ horizon as described for the Miami series. Material comparable to that of the A₂₂ horizon also occurs as a film on the aggregates in the underlying B₁ horizon in the gray-brown podzolic soils of New York in the manner described by Brown and Thorp for the Miami series. The thickness of the A₂₂ horizon does not vary greatly with acidity, ranging mainly from 3 to 6 inches.

The brown podzolic soils are considered zonal soils of humid cool-temperate regions intermediate between the regions of gray-brown podzolic soils and podzols. In New York they occur in region 1 (fig. 1) and as minor areas on acid materials in region 2. They are confined to parent materials in which carbonates

are low or are entirely absent. If calcareous material is present, it lies at a depth generally beyond the reach of most plant roots.

These soils are more closely related morphologically to podzols than to the gray-brown podzolic soils in New York. They characteristically have a layer of humus essentially unmixed with mineral soil on the surface, and the underlying A₁ horizon is very thin and weakly expressed. There is generally some evidence of an incipient *Bleicherde*, commonly restricted under the normal hardwood



FIG. 1. GENERAL DISTRIBUTION OF NORMAL SOILS OF NEW YORK

1. Dominantly brown podzolic soils with weakly developed podzols at the higher elevations; 2. Dominantly gray-brown podzolic soils with brown podzolic soils or weak podzols on acid materials; 3. Dominantly podzols.

vegetation to light gray specks in the thin A₁ horizon. Wherever a large hemlock occurs, however, a *Bleicherde* $\frac{1}{8}$ to $\frac{1}{4}$ inch thick is generally conspicuous. The B horizon lies immediately under the A₁, and its strong brown or yellowish brown color suggests a weak sesquioxide accumulation comparable to that in well-developed podzols. There is generally no evidence of an accumulation of sticky and plastic clays such as occur in the gray-brown podzolic soils. The modal profile of this group in New York is essentially that described by Lyford (9) for

the brown podzolic soils in New England. Although Lyford did not mention the presence of an incipient *Bleicherde*, he described light gray mineral particles in the A₁ horizon of brown podzolic soils of New England. The author has seen the *Bleicherde* of moderately developed podzols almost completely masked by organic matter in both New York and New England where forests have been subjected to severe cutting. In these cases, the mixing of organic and mineral material produces an A₁ horizon similar to that found on brown podzolic soils except for a greater proportion of light gray mineral particles.

Podzols are considered zonal soils of cold-temperate humid regions. In New York, strongly expressed podzols are confined mainly to region 3 (fig. 1) in the Adirondack Mountains and on Tug Hill Plateau, but weakly expressed podzols are common throughout region 1, particularly at the high elevations of the Allegany Plateau and the Catskill Mountains. They also occur in many places in region 2 wherever the parent materials are strongly acid and sandy. They are confined throughout the state to parent materials that contain little or no carbonates. Secondary carbonates may occur deep in the parent material under

TABLE 1
Climatic limits of soil regions of New York (10)

REGION	GROWING SEASON	MEAN TEMPERATURE		MEAN PRECIPITATION	
		ANNUAL	GROWING SEASON	ANNUAL	GROWING SEASON
	days	°F.	°F.	in	in
1	100-175	43-49	60-66	33-45	17-20
2	130-180	43-50	60-67	30-45	14-20
3	85-145	35-45	58-64	40-60	17-22

some strongly developed podzols, and some of the podzols in the northern part of the state may have weakly calcareous primary materials at considerable depth.

Well-developed podzols are characterized by a mor humus layer, a very strongly leached gray A₂ horizon that is sharply differentiated from the underlying layers, an accumulation of organic matter and sesquioxides in the underlying B₂₁ horizon, and an accumulation of sesquioxides in a B₂₂ horizon. Sesquioxides decrease with depth until the parent material is encountered at about 2 feet. The soils are strongly or very strongly acid throughout the solum. The *Bleicherde* is commonly 2 to 4 inches thick in New York, but in some places on very coarse siliceous material in northern New York, it is as much as 20 inches thick, and the underlying B horizon is cemented into a distinct *ortstein*. These profiles in New York correspond well with those of New England podzols as described by Lyford (9).

FACTORS OF SOIL FORMATION

Differences of climate are associated with differentiation between brown podzolic soils and podzols on similar materials in New York. Climatic limits of the regions shown in figure 1 are given in table 1. It will be noted that, although

the ranges given for the brown podzolic and podzol areas overlap somewhat, the region of podzols generally has a shorter growing season, lower temperatures, and higher rainfall. On the hilltops of region 1, weakly expressed podzols occur on parent materials similar to those that underlie brown podzolic soils in the valleys of the same region. Similar materials in northern New York, where temperatures are lower and rainfall is slightly greater, give rise to more strongly expressed podzols.

The profiles of these two groups have essentially the same kind and arrangement of horizons. In the brown podzolic soils the horizons are very weakly expressed; in the podzols, they are strongly expressed. The formation of either soil is undoubtedly dependent upon the development of strong acidity. Both soils occur only on materials that were originally acid or on materials from which carbonates have been leached to depths generally beyond the reach of the natural vegetation. Tree species that return small quantities of bases generally dominate on both; the proportion of very low-calcium species is generally greatest where the strongest podzols occur. In the opinion of the author, the objective of the natural classification of soils would be served better if the brown podzolic soils were classified as weakly expressed podzols instead of as a separate great soil group.

The kind and arrangement of horizons in the gray-brown podzolic soils are greatly different from those in podzols. Table 1 indicates, however, that in New York the climatic range of the region of gray-brown podzolic soils covers most of the range of the region of brown podzolic soil and a large part of that of the podzols. Consequently, one cannot attribute the development of the gray-brown podzolic profile in New York to climatic factors that are at present distinctly different from those under which brown podzolic soils or podzols have developed. The gray-brown podzolic soils are associated with calcareous parent materials, whereas the brown podzolic soils and podzols are associated with non-calcareous materials. Differences of vegetation are also associated with these differences in parent material: table 2 shows that low-calcium species comprise almost half of the present cutover forest on the Bath soils, which are weakly expressed podzols. On the gray-brown podzolic Honeoye soils, they comprise only about one-eighth of the present stand, and high-calcium species make up almost 40 per cent. Chandler (4) has reported similar relationships in New York. Although not conclusive evidence of the composition of the forest under which these soils developed, these data are indicative of relationships that might have existed before the forests were cut. These two covarying factors, parent material and vegetation, are the only factors of soil formation that are consistently different on areas of gray-brown podzolic and brown podzolic soils at present.

Wherever acid parent materials occur in the region dominated by gray-brown podzolic soils, brown podzolic soils or weak podzols have developed. This suggests that essentially all of New York, with the possible exception of the lower Hudson Valley, is a region in which strictly "zonal" soils are either brown podzolic soils or podzols. The gray-brown podzolic soils that do occur in New York would appear to be "zonal soils" in intrazonal position, apparently as a result of the

calcareous nature of the parent material. This is not true farther south in eastern United States, where gray-brown podzolic soils occur on both calcareous and noncalcareous parent materials.

TABLE 2

*Distribution of tree species according to foliar calcium content on Honeoye and Bath silt loams on second-growth woodlots in western and southern New York**

SPECIES	PERCENTAGE OF ALL TREES		PERCENTAGE OF BASAL AREA	
	Honeoye	Bath	Honeoye	Bath
<i>Foliar calcium greater than 2 per cent</i>				
Ash, white— <i>Fraxinus americana</i>	4.4	1.9	4.2	1.6
Aspen— <i>Populus</i> sp.	—	6.1	—	8.6
Basswood— <i>Tilia americana</i>	14.7	2.2	20.8	5.4
Cherry, black— <i>Prunus serotina</i>	1.5	0.2	2.2	0.1
Hickory, bitternut— <i>Carya cordiformis</i>	10.3	—	8.4	—
Hop hornbeam— <i>Ostrya virginiana</i>	5.9	4.5	1.3	2.3
Locust, black— <i>Robinia pseudoacacia</i>	1.2	—	2.2	—
Total, high-calcium species	38.0	14.9	39.1	18.0
<i>Foliar calcium 1-2 per cent</i>				
Birch, black— <i>Betula lenta</i>	—	9.8	—	7.1
Birch, yellow— <i>Betula lutea</i>	0.1	1.3	0.2	0.8
Cucumber tree— <i>Magnolia acuminata</i>	—	0.3	—	0.2
Elm, american— <i>Ulmus americana</i>	6.2	—	5.1	—
Hickory, shagbark— <i>Carya ovata</i>	—	0.2	—	0.1
Maple, sugar— <i>Acer saccharum</i>	32.8	21.1	33.4	14.6
Oak, white— <i>Quercus alba</i>	—	0.6	—	0.3
Oak, red— <i>Quercus borealis</i> var. <i>maxima</i>	5.8	3.7	9.0	10.6
Total, medium-calcium species	44.9	37.0	47.7	33.7
<i>Foliar calcium less than 1 per cent</i>				
Beech, american— <i>Fagus grandifolia</i>	16.5	27.4	12.7	27.3
Hemlock, eastern— <i>Tsuga canadensis</i>	—	0.7	—	2.6
Maple, red— <i>Acer rubrum</i>	0.1	19.5	0.1	18.2
Total, low-calcium species	16.6	47.6	12.8	48.1
<i>Unclassified</i>				
Cherry, sweet— <i>Prunus avium</i>	0.4	0.5	0.3	0.2
Butternut— <i>Juglans cinerea</i>	0.1	—	0.1	—
Total, unclassified	0.5	0.5	0.4	0.2

* From Foster, D. L., Hardwood tree growth on three soil types in central New York. 1947. [Unpublished thesis. Copy on file Cornell Univ. Library, Ithaca, N. Y.]

GEOGRAPHIC PROFILE SEQUENCES

The parent materials of the soils of New York are almost without exception deposits of glacial origin. The ground moraine is a mixture of many kinds of rocks over which the ice passed, but the relative proportions of different rocks in the till varies generally in inverse proportion to the distance from their outcrops. It is possible, therefore, to sample a geographic sequence of profiles developed on materials in which the proportion of a given rock constituent decreases progressively in a given direction. This has made it possible to study sequences of profiles from

the modal profile of one great soil group through various intergrades to the modal profile of another great soil group.

Brown forest-gray-brown podzolic sequence

In 1947, studies of physical and chemical properties of the Honeoye soils of the gray-brown podzolic group were begun in Ontario and Yates Counties. Ten areas were selected from among woodlots on soils mapped as members of the Honeoye series. In intimate association with the Honeoye soils are small areas on which the pH of the upper part of the soil is higher than normal for the Honeoye series. These small areas occur near the outcrop of the limestone from which much of the calcareous material in the Honeoye soils is derived, and the parent materials are consequently abnormally high in carbonates. Although separation of such small areas from the Honeoye series was not feasible in routine detailed mapping, the soils in these areas are members of a series mapped in other parts of the state under the tentative name of *Fenner*.³ Three sites were selected on

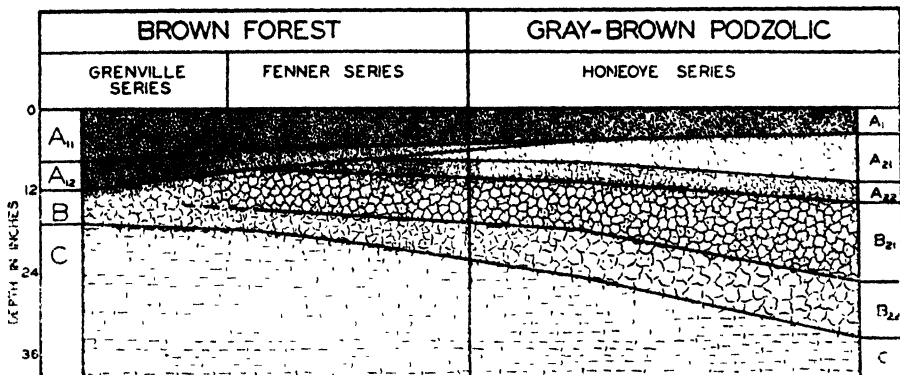


FIG. 2. A BROWN FOREST-GRAY-BROWN PODZOLIC PROFILE SEQUENCE

these Fenner soils; the other seven covered the range of acidity of the Honeoye series. A detailed description of each profile was taken at the time of sampling, and when these data were assembled it was found that the ten profiles could be arranged as members of a continuous series representing the transition from brown forest to well-developed gray-brown podzolic soils. This geographic sequence is shown diagrammatically in figure 2. Although the Grenville series does not occur in the area studied, its profile is shown at the left side of figure 2 to indicate the relationship of the Fenner series to a modal brown forest soil. The soil represented by the extreme right side of the diagram is an intergrade to the gray-brown podzolic Lansing soils, which are derived from only mildly calcareous materials.

As one goes from the modal brown forest soil, as represented by the Grenville series, to its intergrade with gray-brown podzolic soils, as represented by the Fenner series, one finds that the A₁ horizon becomes thinner and less strongly

³ Tentative name, not correlated.

granular but that its reaction remains about neutral. An incipient leached zone comparable to the A_{22} horizon of gray-brown podzolic soils appears below the accumulation of organic matter but is partly masked by mixing of organic matter from the A_1 horizon above. This horizon is distinguishable mainly by slightly lighter color than the material above or below it and by weakly developed coarse crumb structure. It also is neutral. The B horizon takes on the well-developed medium nuciform structure characteristic of gray-brown podzolic soils but is not distinctly finer in texture than the horizons above. The lower part of this B horizon has less well-developed nuciform structure and is mildly alkaline or weakly calcareous. Thus, the Fenner series has a structural profile typical of gray-brown podzolic soils but has pH and textural profiles typical of brown forest soils.

As one goes from an area of Fenner soils into an area of Honeoye soils, one finds that the A_1 horizon retains its neutral reaction but loses its distinctly granular structure and becomes thinner and crumb-structured. The A_{12} horizon disappears and is replaced by a slightly acid A_{21} horizon, which has a faint tinge of yellowish brown. The A_{22} horizon becomes distinctly pale brown, takes on a very weak very thin platy structure, and becomes slightly acid. The B_{21} horizon retains its well-developed medium nuciform structure, and the clay fraction increases. The B_{22} horizon takes on a moderately well developed coarse nuciform structure and also becomes distinctly clayey. The pH increases with depth throughout the B horizon in the Honeoye soil, and the B_{22} may be weakly calcareous. The parent material is strongly calcareous.

An array of profiles from the least acid to the most acid extremes of the Honeoye series (left to right in figure 2) shows the following changes: (a) The entire solum deepens, the most striking increase in thickness being in the A_{21} and B_{21} horizons. (b) The A_1 horizon retains its moderately developed medium crumb structure and near-neutral pH, but the yellowish-brown A_{21} horizon becomes increasingly acid, reaching a pH near 5.0 where the Honeoye soils grade into the Lansing series at the point represented by the right side of the diagram. (c) The A_{22} retains its original thickness but becomes increasingly acid, generally being slightly less acid than the A_{21} . (d) The B_{21} horizon thickens but does not increase in clay content, and pale brown silty coatings on the aggregates in the upper part of the horizon extend to greater depths and become thicker as acidity of the A_{22} horizon increases. The appearance in the profile represented by the right side of figure 2 is suggestive of encroachment of the A_{22} horizon on the B_{21} . (e) The B_{22} horizon generally becomes the most clayey horizon in the profile and rests abruptly on the highly calcareous parent material.

This geographic succession of profiles is repeated in western and central New York wherever parent materials progressively decreasing in calcium carbonate content occur. It may be observed, for example, on glacial outwash in going from the Palmyra series to the Howard series.

Gray-brown podzolic-brown podzolic sequence

In 1948 a study of the sequence of profiles from the gray-brown podzolic Ontario series to the brown podzolic Sodus series was undertaken in Cayuga and

Oswego Counties. Six profiles were selected specifically to represent the modal profile of each series and intergrades representing the high- and low-lime extremes. In this area the Ontario series grades by almost imperceptible stages into the brown podzolic Sodus series, and that gradation is associated with a progressive decrease in the lime content of the parent material. This sequence of profiles is represented diagrammatically in figure 3.

Profile 1 at the left margin of the diagram is essentially comparable to the modal profile of the Honeoye series of figure 2. The A_2 horizon is only slightly acid; the B horizon is characterized by a strong accumulation of clays. The A_2 horizon may be subdivided into an upper yellowish brown and a lower grayish brown or pale brown layer. The nuciform structure typical of gray-brown pod-

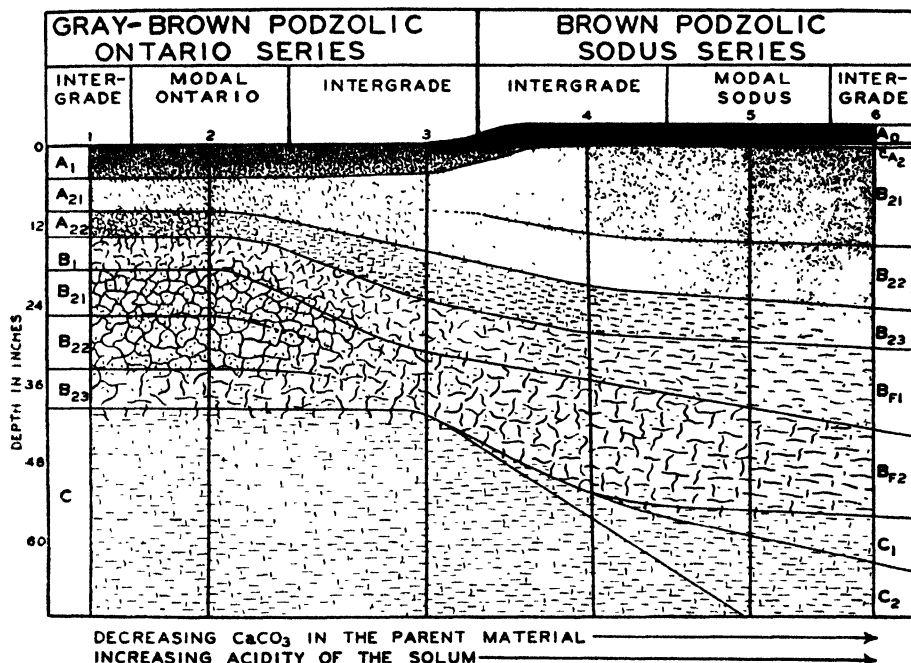


FIG. 3. A GRAY-BROWN PODZOLIC-BROWN PODZOLIC PROFILE SEQUENCE

zolic soils is strongly expressed in the B, and pH increases with depth until calcareous material is encountered in the lower part of the B_{23} horizon.

Within the range of the Ontario series as illustrated in figure 3, the following variations in the solum are correlated with decreasing calcium carbonate in the parent material: (a) The A_{21} horizon thickens, becomes more distinctly yellowish brown, and becomes strongly acid, with a pH near 5.0 in profile 3. (b) The A_{22} horizon increases slightly in thickness and loses its crumb or fine nuciform structure, becoming distinctly platy. In profile 3 it has a pH near 5.0. (c) The nuciform structure of the B_1 horizon becomes less distinct, and materials comparable to that of the A_{22} horizon coats the outsides of the aggregates, giving the horizon an appearance of degradation. The pH of this horizon also decreases to

near 5.0. (d) The nuciform character of the B_{21} and B_{22} horizons is replaced by a weakly developed coarse blocky structure, but the clayey nature is retained. (e) Subdivisions of the B_2 horizon become indistinct. The pH in the B horizon increases with depth from near 5.0 at the top to 7.0 at the bottom in profile 3. In profile 3, the upper part of the soil resembles the solum of a brown podzolic soil except for the humus layer, and the lower part of the solum retains the character of a gray-brown podzolic B horizon. Profile 3 has every appearance of a weak brown podzolic solum developed in the upper part of a gray-brown podzolic soil.

In profiles 4, 5, and 6 the upper part of the solum is definitely brown podzolic. The mull humus layer, which was nearly neutral in profiles 1, 2, and 3, is replaced by a very strongly acid matted mor humus layer almost unmixed with mineral soil. Faint evidence of an incipient *Bleicherde* is apparent in profile 5, and a distinct $\frac{1}{2}$ -inch layer occurs in profile 6. The position of the gray-brown podzolic A_{21} horizon is occupied by yellowish-brown silty-feeling B_{21} and B_{22} horizons typical of brown podzolic soils. The intensity of the yellowish brown color of this layer increases from profile 4 to profile 6 and decreases in all profiles with depth. In profiles 4 and 5 an indistinctly platy horizon that resembles the A_{22} horizon of profile 3 occurs below the B_{22} , but in profile 6 it is replaced by a layer with the fine crumb structure and pale yellowish brown color of the lower part of the B horizon of brown podzolic soils. Below this layer are two horizons, represented in the diagram by B_{F1} and B_{F2} , which become less clayey from profile 4 to profile 6. These layers are firm in place and distinctly platy. Little difference in texture between them and the horizons above can be determined by feel in profile 6, but examination under the microscope shows accumulations of clayey materials in the centers of the aggregates. The outsides of the aggregates are pale brown silty or sandy material similar in appearance to that of the A_{22} horizon of the Ontario series. The pH is between 5.0 and 5.5 throughout these horizons in profile 6. These horizons are not typical of brown podzolic soils and occur below the normal depth of brown podzolic solums. On the basis of their appearance of degradation, it is suggested that they are fossil remnants of formerly clayey B horizons that are losing their clays under the influence of intense acid leaching. If clays are being lost, their removal must be accomplished by chemical decomposition and not by translocation unchanged, because no zone of clay accumulation occurs below. Depth to carbonates also increases from profile 4 to profile 6, and horizons that are physically similar to the parent material but from which free carbonates have been lost occur immediately under the fossil B. In profile 6, the pH of the C_1 horizon is about 6.0, and that of the C_2 is between 7.0 and 7.5. The material is free of carbonates to a depth of 8 feet.

SOIL GENESIS

Several explanations of the profile sequences described are possible. The simplest explanation would be that the observed geographic sequences are natural transitions from one environment to another. Such transitions occur between all geographically associated but morphologically dissimilar soils. The sequences observed in New York are apparently the direct result of progressively decreasing

content of carbonates of the alkaline earths in the parent materials, and it might be assumed that each of the profiles observed is an equilibrium product peculiar to the particular composition of parent material at the spot studied. That possibility cannot be denied on the basis of morphological evidence in the Grenville, Fenner, Honeoye, and Ontario series. In the Sodus series, however, there is good reason to doubt its validity on the basis of the morphological evidence of partial disintegration of a horizon of clay accumulation deep in the solum. Two explanations of the occurrence and apparent disintegration of that clay-bearing layer may be advanced.

It might be assumed from the observed correlation between high content of divalent bases and occurrence of the gray-brown podzolic profile that a material high in divalent bases is a prerequisite of the *development* of a gray-brown podzolic soil under the climatic conditions of the area. A mechanism by means of which silicate clays might be translocated from the A to the B horizon in soils at relatively high pH has been proposed by Pallmann *et al.* (11) for similar soils in Switzerland. As evidence that some such process may be operative, it can be shown that (a) clays in the slightly acid A₂ horizon of gray-brown podzolic soils of New York go into stable suspension in water, (b) those in the weakly alkaline or neutral B horizon do not, and (c) suspensions of clays from the A₂ are flocculated by addition of suspensions of clays from the B. Absence of the gray-brown podzolic type of profile on materials near pH 5.0 would be evidence that relatively high base status is a prerequisite of development of the gray-brown podzolic type of profile under the climatic conditions of the area. One cannot postulate this requirement for areas with slightly warmer climate farther south, where gray-brown podzolic soils occur generally on acid parent materials.

A second possibility, which deserves serious consideration, is that the gray-brown podzolic soils of the area were developed under a warmer climate than exists today—a climate comparable to that which now prevails farther south in the main region of gray-brown podzolic soils. There is good evidence in Europe of the occurrence of an appreciably warmer “climatic optimum” of considerable length 4,000 to 6,000 years ago (7, 8). The evidence in North America is less conclusive, but Deevey (6) considers it adequate at least to suggest distinct parallelism between climatic changes in Europe and North America. Much of the supporting evidence is in the form of pollen analysis of peats and sediments, which, in itself, is indicative of a vegetation more like that of gray-brown podzolic regions than is found today on acid material. It may be postulated that a warmer climate and associated types of vegetation might have resulted in development of gray-brown podzolic soils on most parent materials in the area and that the observed B_z horizon of the Sodus soil in figure 3 is a remnant of a gray-brown podzolic B horizon from a period of warmer climate. Additional support for this explanation is furnished by isolated examples of a comparable horizon on some moderately acid materials in the Mohawk Valley of New York and on some strongly acid materials south of the glaciated area in Pennsylvania.⁴ If this explanation were accepted, one could attribute the existence of well-developed

⁴ From private correspondence with W. H. Lyford of the Soil Survey Division, U. S. Department of Agriculture.

gray-brown podzolic soils, like those of the Honeoye series of figure 2, to the effectiveness of high base status in *inhibiting* destruction of the profile and development of a brown podzolic solum.

CHANGES OF SOIL PROFILES WITH TIME

Whether one postulates development of the gray-brown podzolic profile under a warmer climate than now exists or as a result of high base status under a climate similar to that of the present, morphology like that of the Sodus and Ontario soils of figure 3 suggests that brown podzolic solums are developing in the profiles of older gray-brown podzolic soils. As a working hypothesis, it is suggested that progressive stages in the development of soils in central and western New York may parallel the observed geographic sequences presented in figures 2 and 3. This hypothesis is based on the part bases would be expected to play in the soil-forming processes involved.

It is suggested that the first soil to develop on material high in divalent bases would be a brown forest soil comparable to that of the Grenville series of figure 2. Accumulation of organic matter would occur under the influence of high levels of mineral nutrients, vigorously growing vegetation, and very active soil fauna. Available nitrogen would be under heavy drain by the vegetation, minimizing leaching losses, and mixing by soil fauna would materially offset the translocation of clays. Eventually a condition should be established under which losses and additions of nitrogen would be approximately balanced and organic matter, which is largely covariant with nitrogen in any given environment, would be at its maximum level. This, in many respects, would be comparable to the conditions postulated by Pallmann *et al.* (11) for *reife Braunerde* of Switzerland.

With time, the gray-brown podzolic solum might be expected to develop on calcareous materials if the mechanism described by Pallmann is substantially correct. If one postulates a period of warmer climate than now exists, similar profiles might have developed on acid materials also. It is suggested that the succession of profiles with time might be essentially that illustrated by the sequence from the Grenville to the Honeoye series in figure 2 on calcareous parent materials. It is, perhaps, significant that in going from Guelph to the Quebec boundary in the province of Ontario, Canada, one finds progressively decreasing degrees of expression of the gray-brown podzolic profile on calcareous parent materials. This sequence lies in the direction of glacial recession, and materials at the Quebec boundary are certainly appreciably younger than those at Guelph. The evidence is not conclusive, however, because differences of time are confounded with differences of climate.

Granted the existence of a gray-brown podzolic profile, one may logically expect its eventual replacement by a brown podzolic soil under present climatic conditions. Large amounts of bases, of which calcium is dominant, are being lost from areas of calcareous glacial deposits (5). One would expect this drain eventually to deplete bases in the solums of at least some soils in spite of return of nutrients by vegetation and removal of leached material by normal geologic

erosion. The return of bases by vegetation may offset leaching losses in the surface layers, but eventually a point should be reached when the calcium cycle would be inhibited by depletion of bases throughout the rooting zone. This is consistent with observed conditions in gray-brown podzolic soils, which generally have A_1 horizons near neutrality and at least moderately acid A_2 horizons in New York. The differentiation of the A_2 horizon into an upper yellowish brown layer and a lower pale brown subhorizon is not distinct in the Ontario series of figure 3 unless the pH is below 6.0. It is suggested that the yellowish brown A_{21} horizon in these soils is an incipient B_{21} horizon of a brown podzolic soil initiated by the release of sesquioxides under conditions of moderate acidity. As bases continue to be lost, the A_{21} horizon would be expected to increase in thickness, as it does from profile 2 to 3 in figure 3. The morphology of profiles 3 and 4 suggests that the less acid A_{22} horizon sinks into the B as clays are translocated still more deeply into the profile. At some stage in the depletion of bases, the soil would no longer support vegetation that returns large quantities of bases, the humus layer would change from a mull to a mor, and the moderately intense acid leaching of the brown podzolic soils would be initiated. This is the interpretation suggested from profile 4. From this stage on, deterioration of the gray-brown podzolic solum and establishment of the brown podzolic profile should be rapid. If the mechanism proposed by Pallmann (11) for translocation of silicate clays is substantially accurate, clays lost from the upper part of the B horizon would be expected to be reprecipitated near that point in the profile where calcareous material is encountered in soils like that of profile 3. With time, however, leaching of bases might proceed at a sufficiently faster rate than their return that the entire fossil B would become acid, as in profiles 5 and 6 of the Sodus series. Under these conditions, the silicate clays themselves might break down instead of moving unchanged to lower horizons.

Even though the foregoing hypothesis should prove to be correct in principle, it does not follow that soils on all materials in all topographic situations would follow the same course. Losses of bases and their return may vary so greatly on materials of different texture, different permeability, and different composition that at least quasi-equilibrium may be postulated on various sites for most of the profiles described. It is not suggested that gray-brown podzolic soils everywhere are temporary things that will be succeeded by podzols or that all gray-brown podzolic soils of New York will necessarily be changed to brown podzolic soils or to podzols. It is suggested that the hypothesis presented may explain the morphology of those soils that have brown podzolic or podzol solums in the upper part and clayey layers similar to gray-brown podzolic B horizons below. It is also suggested that at least some of the gray-brown podzolic soils of New York may be in the early stages of transformation to brown podzolic soils. The hypothesis applies only to regions where brown podzolic soils or podzols occur on acid materials, but the occurrence of profiles somewhat similar to that of the Sodus series in Michigan (12) suggests that it may apply in a much larger area than the State of New York.

SUMMARY

Brown forest, gray-brown podzolic, brown podzolic, and podzol profiles occur in normal positions in New York. The gray-brown podzolic and brown forest soils are restricted to parent materials high in bases, and brown podzolic soils and podzols, to acid materials. Differences of present vegetation are also associated with these differences in parent material. The distribution of gray-brown podzolic and brown podzolic soils is not correlated with measured differences in climate. Differences of climate, especially temperature, are associated with the distribution of brown podzolic soils and podzols on similar materials. A continuous geographic sequence of profiles from the brown forest through gray-brown podzolic to brown podzolic profiles is described for a continuous series of parent materials of progressively decreasing carbonate content. Profiles of this sequence provide evidence that at least some brown podzolic soils have developed in the solums of former gray-brown podzolic profiles. The presence of gray-brown podzolic soils in the area studied may be explained either by processes involving a high base status or by postulation of a period of warmer climate than exists now. A working hypothesis is presented that the geographic sequence observed may be duplicated by a chronological succession of profiles in those cases where the loss of bases by leaching is not offset by the return of bases by vegetation.

REFERENCES

- (1) BALDWIN, M. 1927 The gray-brown podzolic soils of the eastern United States. *First Internatl. Cong. Soil. Sci. Proc. and Papers Comn.* V: 276-282.
- (2) BROWN, I. C., AND THORP, J. 1942 Morphology and composition of some soils of the Miami family and the Miami catena. U. S. Dept. Agr. Tech. Bul. 834.
- (3) CHANDLER, R. F., JR. 1939 The calcium content of the foliage of forest trees. N. Y. (Cornell) Agr. Exp. Sta. Mem. 228.
- (4) CHANDLER, R. F., JR. 1941 The amount and mineral nutrient content of freshly fallen leaf litter in the hardwood forests of central New York. *Jour. Amer. Soc. Agron.* 10: 859-871.
- (5) CLARKE, F. W. 1916 The data of geochemistry. U. S. Geol. Survey Bul. 616.
- (6) DEEVEY, E. S., JR. 1944 Pollen analysis and history. *Amer. Scientist* 32: 39-53.
- (7) FLINT, R. F. 1947 Glacial Geology and the Pleistocene Epoch. John Wiley & Sons, New York.
- (8) GODWIN, H. 1934 Pollen analysis. An outline of the problems and potentialities of the method: II. *New Phytol.* 33: 325-358.
- (9) LYFORD, W. H., JR. 1946 The morphology of the brown podzolic soils of New England. *Soil Sci. Soc. Amer. Proc.* 11: 486-492.
- (10) MORDOFF, R. A. 1925 The climate of New York State, N. Y. (Cornell) Agr. Exp. Sta. Bul. 444.
- (11) PALLMANN, J., FREI, E., AND HAMDI, H. 1943 Die Filtrationsverlagerungen hochdisperser Verwitterungsprodukte im Bodenprofil einiger Glieder der schweizerischen Braunerdeserie. *Ber. Schweiz. Bot. Gesell.* 53A: 175-191.
- (12) VEATCH, J. O., AND MILLAR, C. E. 1934 Some characteristics of mature soils in Michigan. *Amer. Soil Survey Assoc. Bul.* 15: 42-44.

BOOKS

Garden Soils, Their Use and Conservation. By ARTHUR B. BEAUMONT. Orange Judd Publishing Company, Inc., New York, 1948. Pp. 280. Price \$3.50.

This readable and well-illustrated book is confined to soils and the importance of a knowledge of soils in successful gardening. Selection of the best possible soil for a garden is stressed, and information necessary in making such a selection is presented. Ways of improving the soil are adequately treated. Tillage and soil conservation practices from the practical standpoint of the home gardener are discussed, as well as the use of composts and fertilizers. Any person wanting to know how to manage garden soils in a manner to produce abundant crops will benefit from reading this book. It reflects both the long practical experience of the author as a gardener and his lifelong scientific study of soils.

JOHN P. JONES

Abstracts of Recent Published Material on Soil and Water Conservation. By J. H. STALLINGS. U. S. Department of Agriculture, Washington, D. C. 1949. Pp. 82.

Current information on soil and water conservation, as developed by those who are actively engaged in this work, is contained in this mimeographed report. The work of some 200 men is reviewed. A great many very interesting bits of important information are given. This publication supersedes "Research Summaries" that was previously issued by the Conservation Service in seven parts. It is believed that it will appear twice a year.

Biochemical Preparations. Volume 1. By HERBERT E. CARTER. John Wiley and Sons, Inc., New York, 1949. Pp. 76. Price \$2.50.

This is the first of a series of volumes designed to give precise directions for the preparation of organic substances that are of special interest and importance to research workers in biochemistry. This volume deals with 16 organic substances, each of which is discussed under the following headings: principle, starting material, procedure, properties and purity of product, and methods of preparation. Each of these procedures has been submitted by a specialist in that compound and all of them have been checked by other workers in that field of study. Additional references, together with occasional explanatory notes, are shown at the bottoms of the pages. Isolation methods are emphasized, but methods of synthesis are also shown when thought preferable. An additional volume will be published every 12 to 16 months. Material for volumes 2 and 3 is now being solicited. This will be a very valuable series of volumes which all biological chemists will want at hand for ready reference.

Dynamics of Vegetation. By FREDERIC E. CLEMENTS. The H. W. Wilson Company, New York, 1949. Pp. 296, plates 70. Price \$3.75.

By compiling these selections from the writings of Dr. Clements, an outstanding ecologist who has made many highly important contributions to our thinking

and practice in this field of study, B. W. Allred and Edith S. Clements have performed a highly important service to soil-plant scientists in this country. The book is divided into eight chapters that deal with plant succession and human problems, competition in plant societies, plant indicators, nature and structure of the climax, relict method in dynamic geology, climaxes, succession, and conservation, climatic cycles and human populations in the Great Plains, and ecology in the public service. The plates, made up usually of two or more illustrations, are exceptionally well chosen and add much to the presentation. A very helpful glossary of terms is appended. The book is a mine of useful information and makes very interesting and instructive reading.

Etude Préliminaire des Sols du Périmètre Irrigable des Srarhna. By GEORGES BRYSSINE, ANDRÉ FOURY, AND GEORGES GRILLOT. Service de la Recherches Agronomiques et de l'Expérimentation Agricole, Rabat, 1948. Pp. 54, maps 3, plates 6.

This paper-bound report gives the geography and climate of the area, some typical soil profiles, with schematic presentation in color, a list of native plants, a generalized soil map, and some excellent aerial views. The text is well presented, and the illustrative material is informative and interesting.

Gloucester, Somerset and Wiltshire. A Geographical Analysis. By Reconstruction Research Group, University of Bristol, 1949. Pp. 12, maps 3. Price (paper bound) 8/6.

Three large maps, on a scale of one-quarter inch per mile and in color, are the essential part of this publication. One of these maps shows the topography, a second shows the land classification, and the third is a composite based on the other two and on features of special interest. The purpose is to decide which land should be retained for agriculture, which should be employed for forestry, park, and scenic purposes, and which might well be devoted to industry. Among these are intermediate classes of land that might be used for one or the other purpose as conditions warrant. Specialists in land-use mapping will find this report of special interest.

The Periodic Partial Failures of American Cottons; Their Causes and Remedies. Scientific Monograph No. 2, Revised Second Edition. By R. H. DASTUR. The Indian Central Cotton Committee, Bombay. Pp. 172, figs. 30. Price Rs. 6.

This monograph presents findings on partial failures of American cottons in the Punjab. It deals primarily with a disease known as "tirak" that developed on a serious scale in 1919. The leaves of affected plants first turn yellow and then deep red, and are shed prematurely. The bolls open incompletely, the seed do not develop, and the fiber is of no value. Tirak was brought under control on sandy soils by use of sulfate of ammonia. On soils with saline subsoils, application of extra water at the beginning of the flowering stage was useful. A simple method of testing the leaves for nitrogen deficiency was developed. This consists of extracting leaf discs with hot water, adding a few drops of an aqueous solution of osmic acid and two drops of dilute sulfuric acid. If a blue-green to dark brown

color develops, the crop requires nitrogen. If the extract remains yellow or orange-red, no nitrogen is required. Some 80 references are appended. The monograph should be of considerable interest to those who are concerned with research in the nutrition of the cotton plant.

Photosynthesis in Plants. Edited by JAMES FRANCK AND W. E. LOOMIS. The Iowa State College Press, Ames, 1949. Pp. 500, figs. 129. Price \$7.

This is the second volume of the monograph series of the American Society of Plant Physiologists. It contains the 22 papers that were presented before a symposium on this subject in Chicago. The subject matter includes an introductory statement, photosynthesis under field conditions, products of photosynthesis, diffusion through multiperforate septa, chloroplasts, pigments, photochemistry, chlorophyll studies, processes accompanying chlorophyll formation, quantum requirements, quantum efficiency of photosynthesis in *Chlorella* and in green plants, calorimetric determination of quantum yield, liberation of oxygen from water by chloroplasts, chlorophyll fluorescence as an energy flow-meter, relation of fluorescence to photosynthesis, pattern of photosynthesis in *Chlorella*, tracer researches, C^{14} in photosynthesis, kinetics of a photochemical intermediate, chemical properties of intermediates, and comparative biochemistry of photosynthesis. The list of 34 authors includes many of the best-known names in this field of research. The importance of the photosynthetic process and of the reactions involved is such as to make the subject of tremendous interest, not only to soil-plant scientists but to industrial scientists as well. The book is likely to enjoy a very wide reading.

Plenty of People. Revised Edition. By WARREN S. THOMPSON. The Ronald Press Company, New York, 1948. Pp. 281, figs. 21. Price \$3.50.

One of the volumes of the Humanizing Science Series, this book deals with population pressures, problems, and policies, and how they concern us. The several chapters deal with population growth since 1800, birth and death rates, war and population, population forecasts and distribution, social and economic effects of age changes and of slower population growth, hereditary fitness, minorities, and population policies. The author believes that England, Germany, and Italy have more people than is desirable and that China, Japan, and India can look forward to only the most distressing poverty unless they control population growth. "The satisfactory adjustment of population to resources should be the major factor in the population policy of any country." But "the fact remains that we live in a world where the political aims of one or two countries and the population policies calculated to support those aims will necessarily have to be taken into account in establishing a policy for ourselves." The book merits study.

The Practice of Soil Conservation in the British Colonial Empire. By HAROLD A. TEMPANY. Commonwealth Bureau of Soil Science, Harpenden, England, 1949. Pp. 106, figs. 29. Price 10s.

The purpose of this publication is to consider the problem of erosion in the Colonial Empire and the means by which it is being brought under control. The

work is based on replies received from a questionnaire that was sent to the directors of agriculture in those dependencies where soil conservation practices have been developed. The several chapters deal with methods of soil conservation dependent on the use of earth structure and on cultural practices and the use of living plant material, controlled grazing and livestock management, systems of agriculture, instruments, implements, and machinery, and legislation and administration. A list of 31 references is appended. The illustrations are excellent. Of special interest is the list of grasses and other plants that are being used to protect the land against wind and water erosion.

Rothamsted Experimental Station Report for 1947. Harpenden, England. Pp. 131. Price 3s (foreign postage extra).

The report lists the members of the staff and gives a review of the work done during 1947. During the year, B. A. Keen left to become director of the East Africa Agriculture and Forestry Research Organization. More than 4,000 visitors came to Rothamsted during 1947. They included members of the International Congress of Pure and Applied Chemistry, the Genetical Society, and the Institute of Physics. Among the items reported on are: fertilizer placement for potatoes, use of salt on sugar beets, sodium pyrophosphate as an extractant for soil organic matter, heavy-metal-organic matter complexes, deep and shallow plowing, measuring the separated diffusion of cations and anions, biochemical studies of plant viruses, earthworm investigations, and molybdenum-manganese relationships.

Techniques of Histo- and Cyto-Chemistry. By DAVID GLICK. Interscience Publishers, Inc., New York, 1949. Pp. 531, figs. 158. Price \$8.

This manual of morphological and quantitative micromethods for inorganic, organic, and enzyme constituents in biological materials is designed as a reference for workers specializing in this field of research. The microscopic techniques include freezing-drying preparations of tissue, chemical methods on inorganic elements and radicals, organic substances and groups, and enzymes, and physical methods on fluorescence, emission histospectroscopy, visible and ultraviolet absorption, Roentgen absorption, microincineration, electron microscopy, and radioautography. The chemical techniques include apparatus, colorimetric, titrimetric, gasometric and dilatometric techniques, determination of amounts of biological samples, and deductive methods. The microbiological techniques are mostly concerned with riboflavin. The mechanical separations involve centrifuges, separation of components of *A. punctulata* eggs, and the isolation of cell nuclei, chromatin threads, cytoplasmic particles, chloroplasts, and other cell particulates. The book is exceptionally valuable for laboratory reference, and every chemist and biologist who is concerned with such techniques will want a copy close at hand.

THE EDITORS

NEWS NOTES

INTERNATIONAL COMMITTEE FOR THE STUDY OF CLAYS

(COMITÉ INTERNATIONAL POUR L'ÉTUDE DES ARGILES, CIPEA)

The International Committee for the Study of Clays was organized in London in August, 1948, at the time of the meeting of the International Geological Congress. S. Henin of France was elected chairman, and M. Lepingle of Belgium, secretary. The committee is limited to two representatives from each country. The members of the committee from the United States are R. E. Grim of the Illinois State Geological Survey and W. P. Kelley of the University of California.

The committee is to function through an executive subcommittee, which was designated at the meeting in London as follows: S. Henin, France; M. Lepingle, Belgium; R. E. Grim, U. S. A.; D. M. C. MacEwan, Great Britain.

The committee wishes to include all phases of clay research and work on clay in all specialized fields. Its objects are to bring together a complete documentation of the studies of clays and their means of study, to facilitate contacts between specialists in these studies, and to hold periodic meetings in the course of which all questions relative to clays will be examined and discussed.

For most ready comparison of results and that all the specialists may, in effect, "speak the same language," the committee will facilitate exchange of reference samples among research workers and will make every effort to increase precision in the terminology as well as the methods used in the science of clays.

It is planned that the members of the international committee will effect liaison between the committee and the research workers of their respective countries. In some countries, as in Belgium, France, Great Britain, and Sweden, national committees are being organized, their officers acting as members of the international committee.

Questionnaires on various subjects will be sent by the international committee to the members from each country, who will be responsible for distributing them and obtaining replies.

The first activity of the committee concerns standardization of the differential thermal procedure, and a statement concerning plans for studying the problem is being prepared.

RALPH E. GRIM

BIOLOGICAL ABSORPTION OF PHOSPHORUS

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It has sometimes been observed that addition of undecomposed organic matter to soil may lead to a considerable deficiency in phosphorus available for plants (3, 5, 9, 11). An explanation given for this phenomenon is that microorganisms decomposing organic matter assimilate a large amount of phosphorus into new cell substance. Some investigations on the decomposition of plant residues have shown that, at the beginning of humification, a large part of inorganic phosphorus may be converted into organic compounds, but later after the sources of available energy have been exhausted, mineralization of phosphorus can be detected (1, 8).

Biological immobilization and release of phosphorus during decomposition of organic matter seem to be analogous to those of nitrogen, but the former phenomenon has not been investigated so thoroughly as the latter. In her previous publications (6, 7) the author has treated this problem to some extent. In the present investigation an attempt is made to elucidate the question in greater detail.

PHOSPHORUS REQUIREMENT OF MICROORGANISMS DECOMPOSING ORGANIC MATTER

According to Waksman (12), fungi reassimilate 20 to 60 per cent, on the average 30 to 40 per cent, of the carbon of the organic material that has been decomposed, and bacteria reassimilate between 1 and 30 per cent, on the average about 5 to 10 per cent, of the carbon used as a source of energy. Actinomycetes stand midway between fungi and bacteria, with a reassimilation percentage of 15 to 30. Thus for every 100 units of organic matter, approximately 40 units of fungal material of the same carbon content, 10 units of bacterial cells, and 20 units of mycelia of actinomycetes will be formed when the organic matter is decomposed completely by fungi, bacteria, or actinomycetes, respectively.

The phosphorus content of microbial cell substance varies somewhat, according to the phosphorus concentration of the medium, but may be considered to be about 0.5 to 1.0 per cent of fungal dry matter, and about 1.5 to 2.5 per cent of the water-free bacterial cells and mycelia of actinomycetes (6, 10). On the basis of these values, it can be calculated that approximately the following amounts of phosphorus are assimilated by various microorganisms, when they completely decompose organic material: The fungi assimilate 0.2 to 0.4 per cent, the bacteria 0.15 to 0.25 per cent, and the actinomycetes 0.3 to 0.5 per cent of the organic dry matter consumed.

To verify these conclusions, some experiments were performed with pure and mixed cultures of microorganisms grown in glucose nutrient solution with dif-

ferent phosphorus contents. The nutrient solution for *Aspergillus niger* and for mixed soil flora had the following composition:

Glucose.....	20 gm.
(NH ₄) ₂ SO ₄	2.5 gm.
KCl.....	0.2 gm.
MgSO ₄ ·7H ₂ O.....	0.2 gm.
FeSO ₄	1000 ml.

K₂HPO₄ solution was added to give concentrations of about 0, 0.05, 0.1, 0.2, and 0.3 gm. P per 1,000 ml. of solution, corresponding to 0, 0.25, 0.5, 1.0, and 1.5 per cent of the glucose.

The solutions were sterilized at 0.5 atmosphere pressure for 20 minutes, measured in 100-ml. portions into sterile 500-ml. Erlenmeyer flasks, inoculated with spore suspension of the fungi or with soil suspension, and incubated at 27°C. for 1 week. The cultures were then filtered through weighed paper into 200-ml. volumetric flasks, and the microbial matter was washed with distilled water, dried, and weighed. The solutions with the washings were made up to volume and analyzed for inorganic phosphorus by the colorimetric method (6) and for glucose by the method of Bertrand.

The technique used in experiments with *Streptomyces* sp. differed from the one reported in that ammonium nitrate at the rate of 1.2 gm. per 1000 ml. of solution was used as a source of nitrogen and the amount of glucose nutrient solution was only 50 ml. per flask. The incubation period was 4 weeks.

The results of these experiments are shown in table 1. The values represent averages of duplicates.

Attempts were also made to test various pure cultures of bacteria for assimilation of phosphorus, but difficulties in the estimation of glucose and of phosphorus were so great that no reportable results could be obtained.

Decomposition of glucose was insignificant in cultures without phosphorus, but even the lowest amount of P, 0.2 per cent of the weight of glucose, seems to have been sufficient for vigorous growth of microorganisms and for effective decomposition of glucose in the cultures of *Aspergillus* and of mixed soil flora. The nutrient solution was not the best possible one for *Streptomyces*. The data on phosphorus assimilation by these organisms cannot, therefore, be considered as reliable as those for the fungi and the mixed culture.

As shown in table 1, the amount of available phosphorus has to some extent influenced the ratio between the phosphorus assimilated by the microorganisms and the glucose consumed. Even at the highest concentration of phosphorus, however, these values do not greatly exceed the percentages calculated above. For the mold the ratio ranges from 0.24 to 0.40 per cent, and for the actinomyces 0.27 to 0.63 per cent, thus indicating the different phosphorus requirements of the organisms. In the cultures of mixed soil flora the competition for energy was greater than in the pure cultures, and the microbes, mainly fungi and bacteria, consumed more glucose in proportion to the phosphorus utilized.

The literature reports very few data on the phosphorus requirement of microorganisms decomposing organic matter. The amount of phosphorus assim-

ilated per unit of glucose decomposed by pure cultures of soil fungi can be calculated from data by Chang (2). It ranges from 0.19 to 0.47 per cent in *Aspergillus niger* cultures of different ages and with different concentrations of phosphorus. The phosphorus needs of *Rhizopus nigricans* and of *Trichoderma* sp. seem to be slightly higher in some cultures. With the exception of some irregular cultures, the phosphorus assimilation of *Aspergillus* sp. and of *Penicillium* sp. per unit of glucose decomposed seems to be between 0.2 and 0.9 per cent. Stok-

TABLE 1

Phosphorus assimilation of various microorganisms decomposing glucose in nutrient solution

INITIAL GLUCOSE CONTENT OF FLASK	INITIAL P CONTENT OF FLASK	pH AT END	DRY WEIGHT OF MICROBIAL CELLS	GLUCOSE CONSUMED	P ASSIMILATED	
gm.	mgm.		mgm.	gm.	mgm.	per cent*
Aspergillus niger						
1.98	0	3.05	95	0.39	0	
	5.10	2.19	679	1.98	4.84	0.24
	10.20	2.19	733	1.98	6.86	0.35
	20.40	2.29	744	1.98	7.83	0.40
	30.60	2.41	756	1.98	7.62	0.38
Streptomyces sp.						
0.86	0	7.02	1	0.02	0	
	1.62	5.40	12	0.09	0.44	0.49
	4.16	5.21	17	0.18	0.49	0.27
	8.38	5.20	15	0.20	0.94	0.47
	12.69	5.07	28	0.26	1.63	0.63
Mixed soil flora						
2.52	0	5.41	5	0.28	0	
	5.06	6.31	103	2.26	3.52	0.16
	10.10	6.12	139	2.52	5.81	0.23
	20.20	5.66	355	2.34	8.46	0.36
	30.30	5.10	103	2.18	5.29	0.24

* Of glucose consumed.

lasa (10) reported that the minimum need of *Azotobacter chroococcum* is 2.64 mgm. phosphorus for every gram of glucose consumed. These values do not differ greatly from those calculated above.

The phosphorus requirements of microorganisms during decomposition of organic material of more complex structure are indicated in results obtained by Chang (2, p. 199) in an experiment with cellulose. The ratios between the phosphorus assimilated and the glucose decomposed by mixed flora in sand cultures can be computed from the data (table 2).

The amounts of cellulose decomposed and of organic phosphorus synthesized

increased with increasing concentrations of phosphorus in the cultures. The influence of the quantity of available phosphorus on the ratio between the phosphorus assimilated and the glucose decomposed was less significant. In the youngest cultures the ratio was high, probably indicating an exceedingly vigorous building of new cell substance. In all phosphorus concentrations the ratio dropped below 0.3 per cent by the end of the experiment, because phosphorus released from old cells undergoing autolysis decreased the amount of organic phosphorus in the cultures and the ratio was calculated on the basis of all cellulose decomposed during the entire incubation period. The latter fact must be taken into consideration for the other cultures, though to a lesser degree. The

TABLE 2

Phosphorus assimilation by mixed soil flora during decomposition of cellulose in sand cultures according to the results of Chang (2)

INITIAL CONTENT OF P AS K_2HPO_4		INCUBATION PERIOD	CELLULOSE DECOMPOSED	ORGANIC P SYNTHESIZED	P ASSIMILATED
mgm.	per cent*	days	gm.	mgm.	per cent†
13.7	0.15	14	0.523	3.7	0.71
		28	1.587	5.5	0.35
		42	1.933	6.5	0.34
		79	2.149	7.0	0.33
		121	2.999	7.8	0.26
36.6	0.41	14	0.902	4.9	0.54
		28	2.068	7.2	0.35
		42	2.539	8.5	0.33
		79	2.815	8.6	0.31
		121	4.353	10.1	0.23
91.4	1.02	14	1.225	12.0	0.98
		28	3.242	14.7	0.45
		42	3.715	15.6	0.42
		79	4.372	16.4	0.38
		121	6.185	17.9	0.29

* Of cellulose.

† Of cellulose decomposed.

normal amount of phosphorus needed for consumption of cellulose by mixed soil flora may be considered to range from 0.35 to 0.45 per cent of the amount of cellulose, depending on the concentration of available phosphorus.

The theoretical calculations and the experimental results show that although the amount of phosphorus assimilated per unit of purified organic material decomposed may vary somewhat, it does not, in general, exceed the limits of about 0.15 and 0.5 per cent of the available organic compound in question. As an average value, 0.3 per cent P may be given.

These conclusions apply only to processes taking place under aerobic conditions and with a nutrient supply sufficient for normal growth. If organic material is broken down anaerobically, the amount of energy yielded per unit may be only a small part of that obtained, if the same compound is completely

decomposed. Building of new cell substance and synthesis of organic phosphorus per unit of fermented material also are much less. If there is a lack of other nutrients, especially nitrogen, utilization of phosphorus cannot be normal.

ASSIMILATION AND MINERALIZATION OF PHOSPHORUS DURING DECOMPOSITION OF NATURAL ORGANIC MATERIAL

If organic matter such as plant residues, manure, or microbial substance is broken down by microorganisms, the phosphorus assimilation of the decomposers depends on the amount of energy-yielding material, exactly as in the destruction of purified carbon compounds. The microbes will require approximately 0.3 per cent phosphorus for every unit of organic matter decomposed. They will take the phosphorus from the inorganic or organic compounds of the material in question. Along with the synthesis of new microbial phosphorus, release of phosphorus from dead cells of the organisms and from organic phosphorus compounds of the organic matter will occur as a result of autolysis or influence of hydrolyzing enzymes of microorganisms. As long as available energy-yielding material exists in abundance, the assimilation process will overcome that of release, thus increasing the relative amount of phosphorus found in organic compounds. But as soon as the source of energy becomes low, mineralization of phosphorus in the system may be established.

As approximately 0.3 per cent phosphorus is needed for complete decomposition of pure carbon compounds, natural organic matter containing 0.3 per cent phosphorus, on a dry-matter basis, will usually have a high enough content of phosphorus for rapid and normal decomposition. As soon as the organic phosphorus content of the material exceeds 0.3 per cent, mineralization of phosphorus will become more effective than synthesis.

One must take into consideration that in natural organic material, like plant residues, only part of the carbon compounds are available. For example, lignins are decomposed so slowly by common flora that they have no appreciable effect on the phosphorus assimilation. Thus the critical value for mineralization of organic phosphorus may be much lower than 0.3 per cent in materials high in lignins or other resistant products.

To investigate this problem in greater detail, some humification experiments with plant material were run. Ground air-dry wheat grains and wheat straw were mixed in several proportions to provide various amounts of organic phosphorus. In addition, some experiments were conducted with peat moss instead of wheat straw. The materials were weighed into Neubauer pots, and distilled water was added to give a moisture content of 70 to 80 per cent. According to the nitrogen content of the various mixtures, potassium nitrate solution was added to the water to avoid lack of nitrogen during decomposition. No inoculation was used. The pots were covered with glass plates and incubated at 27°C, for 10 weeks. Phosphorus in samples taken at different intervals was analyzed by a fractionation method developed by the author (7). By successive extractions with hot absolute ethanol, with cold distilled water, and with 0.5 N HCl, phosphorus in phosphatide compounds, in water-soluble organic matter,

in inorganic compounds, in phytin, and in insoluble residue, representing mainly nuclein phosphorus, can be estimated approximately. The results of the fractionations are shown in table 3. The values are calculated on the basis of dry matter.

The columns of organic phosphorus as percentages of residue and of total phosphorus attract especial attention. In the beginning, mixture 1 contained 0.159 per cent organic phosphorus, an amount too small to allow measurable mineralization of phosphorus, when straw was an energy-yielding source. In mixture 6, which contains peat moss instead of straw, a release of phosphorus can be detected after only 9 days. In mixture 1, mineralization does not begin until the amount of organic phosphorus exceeds 0.3 per cent. It can not be proved whether the critical point lies between the ninth and the thirtieth days of humification or in the following period, but in both periods humification seems to be higher than in the other grain-straw mixtures. Probably this is due to the comparatively high content of total phosphorus and to the fact that a large part of its source of energy is made up of easily available carbon compounds arising from the grains. In mixture 2, mineralization seems to begin during the second period of incubation, the critical value being between 0.2 and 0.3 per cent. Mineralization of phosphorus in mixture 3 begins with as little as 0.13 to 0.18 per cent of organic phosphorus, possibly because of more economical utilization of its comparatively scanty supply of phosphorus. In mixture 5, which has an abundant supply of phosphorus, organic phosphorus continues to increase even after it exceeds 0.2 per cent, although its slow rate of increase indicates that mineralization will soon begin. In wheat straw, when incubated alone, no re-release of phosphorus can be detected, the amount of organic phosphorus being below 0.08 per cent even at the end of the experiment.

As mentioned before, the critical value for mineralization seems to be lower in mixtures with peat moss than in those with straw. It is below 0.24 per cent in a mixture consisting of 75 per cent wheat grains and 25 per cent peat moss, and probably below 0.20 per cent in a mixture with 50 per cent of both materials. The corresponding value for a third mixture that contains 25 per cent wheat grains is 0.11 per cent organic phosphorus (not reported in the table).

The relative amounts of organic phosphorus compounds in the various mixtures show that the microorganisms have used phytin and water-soluble organic phosphorus as well as phosphatide compounds as sources of phosphorus, or they have mineralized them without utilization. The rapid increase of insoluble organic phosphorus, mainly representing nuclein compounds, indicates synthesis of new cell substance. This increase continues generally for a time after the critical point of mineralization of organic phosphorus in the whole system is attained.

During humification, the amount of organic phosphorus may sometimes drop below 0.2 per cent of dry matter, but it does not cause any change in the course of the process if mineralization of organic phosphorus has begun. In humified organic matter the supply of available energy is so scant that no considerable assimilation of phosphorus can take place. Besides, the microflora

TABLE 3

Changes in the composition of phosphorus in organic matter during humification

MIXTURE	INCUBATION PERIOD	pH	LOSS OF DRY MATTER	TOTAL P, % OF RESIDUE	INORGANIC P, % OF		ORGANIC P % OF		ORGANIC P			
					Resi- due	Total P	Resi- due	Total P	Soluble in			In- solu- ble
									Abs. etha- nol	Wa- ter	0.5 N HCl	
	days		per cent						%*	%*	%*	%*
1. Wheat grain 75 per cent + wheat straw 25 per cent	0	5.2		0.304	0.145	48	0.159	52	2	11	30	9
	9	8.6	20	0.388	0.180	46	0.208	54	1	6	19	28
	30	7.1	46	0.592	0.218	37	0.374	63	1	18	5	39
	50	9.0	58	0.850	0.580	68	0.270	32	1	13	3	15
	70	9.1	68	0.940	0.749	80	0.191	20	1	5	2	12
2. Wheat grain 5 per cent + wheat straw 50 per cent	0	5.5		0.228	0.109	48	0.119	52	2	12	29	9
	9	8.8	14	0.256	0.050	20	0.206	80	2	14	42	22
	30	9.2	46	0.452	0.148	33	0.304	67	1	18	20	28
	50	8.7	56	0.585	0.302	52	0.283	48	1	13	2	32
	70	8.7	63	0.622	0.422	68	0.200	32	1	10	2	19
3. Wheat grain 25 per cent + wheat straw 75 per cent	0	7.3		0.153	0.074	48	0.079	52	2	15	24	11
	9	9.1	12	0.172	0.038	22	0.134	78	2	24	30	22
	30	8.9	36	0.245	0.065	27	0.180	73	2	23	11	37
	50	9.0	44	0.276	0.085	31	0.191	69	2	21	4	42
	70	9.0	52	0.319	0.101	32	0.218	68	1	23	2	42
4. Wheat straw	0	7.5		0.077	0.037	48	0.040	52	5	21	10	16
	9	8.5	1	0.078	0.023	30	0.055	70	4	11	9	46
	30	9.1	6	0.082	0.019	23	0.063	77	3	14	6	54
	50	8.9	13	0.088	0.015	17	0.073	83	3	15	6	59
	70	8.9	18	0.094	0.015	16	0.079	84	2	15	4	63
5. Wheat straw + 0.6 per cent P as K ₂ HPO ₄	9	8.5	1	0.680	0.630	93	0.050	7	1	1	1	4
	30	9.0	9	0.740	0.598	81	0.142	19	1	3	2	13
	50	8.9	13	0.774	0.582	75	0.192	25	1	8	2	14
	70	9.1	20	0.850	0.632	74	0.218	26	1	5	3	17
6. Wheat grain 75 per cent + peatmoss 25 per cent	0	4.2		0.295	0.137	46	0.158	54	2	11	31	10
	9	4.4	40	0.487	0.246	51	0.241	49	2	11	3	33
	30	8.8	56	0.74	0.546	74	0.194	26	1	7	2	16
	50	8.7	64	0.816	0.649	80	0.167	20	1	4	1	14
	70	8.5	67	0.905	0.752	83	0.153	17	1	2	1	13
7. Wheat straw 5 per cent + peatmoss 50 per cent	0	3.6		0.210	0.094	45	0.116	55	2	11	29	13
	9	4.4	15	0.274	0.080	29	0.194	71	2	8	10	51
	30	6.2	29	0.326	0.191	59	0.135	41	1	8	3	29
	50	6.7	37	0.335	0.244	73	0.091	27	1	3	2	21
	70	6.7	44	0.380	0.280	74	0.100	26	1	9	—	16

* Of total P.

TABLE 4

Mineralization of organic phosphorus in natural organic material during humification

	DECOM- POSITION PERIOD	LOSS OF DRY MATTER	TOTAL P, PER CENT OF DRY MATTER	ORGANIC P, PER CENT OF	
				Dry Matter	Total P
	<i>days</i>	<i>per cent</i>			
Green fodder at 27°C.	0		0.411	0.153	37
	9	26	0.568	0.322	57
	30	42	0.790	0.200	25
	60	58	0.975	0.211	22
	90	60	1.020	0.214	21
Rye straw at 55°C.	0		0.050	0.030	60
	9	20	0.065	0.059	91
	30	25	0.067	0.063	94
	60	35	0.079	0.073	93
	90	48	0.093	0.088	95
Wheat roots at 27°C.	0		0.097	0.059	61
	9	7	0.104	0.063	61
	60	14	0.113	0.072	64
	120	20	0.119	0.079	66
Cattle manure at 35°C.	0		0.455	0.221	49
	30	12	0.522	0.242	46
	60	30	0.646	0.210	33
	150	38	0.735	0.225	31
Horse dung at 23°C.	0		0.485	0.175	36
	9	4	0.504	0.188	37
	30	30	0.696	0.280	40
	60	41	0.825	0.318	39
	90	45	0.864	0.328	38
Fungal material at 27°C.	0		0.577	0.274	47
	9	13	0.669	0.226	34
	30	39	1.013	0.335	33
	60	49	1.131	0.296	26
	90	50	1.146	0.293	26
Wheat bran at 27°C.	0		0.882	0.780	88
	12	39	1.459	0.386	26
	30	64	2.465	0.394	16
	90	73	3.260	0.390	12

of partly humified organic matter consists mainly of bacteria, with a smaller requirement of phosphorus per unit of carbon material decomposed than fungi, which dominate in composts containing plenty of energy-yielding compounds.

Table 4 contains data collected from laboratory experiments with various natural organic materials. The experiments were set up in approximately the

same way as those reported above, with ground air-dry material and additions of sufficient amounts of distilled water and of inorganic nitrogen. The values of the total and of the organic phosphorus are from fractionation results. The green fodder consisted of oats and peas in flower, the rye straw was mature material, the roots of wheat were collected in the autumn. The cattle manure contained 70 per cent fresh feces and 30 per cent fresh urine mixed with a quantity of straw equal to 10 per cent of the fresh weight. The horse dung contained fresh feces without any additions. Fruiting bodies of common mushroom fungi represented fungal material.

In rye straw and wheat roots, inorganic phosphorus was converted to organic compounds during the entire period of decomposition. This process as well as the destruction of organic matter was slow in the compost of wheat roots, but very rapid in the rye straw compost, probably because of the more available carbon material and the high temperature in the latter. The organic phosphorus content of green fodder and that of horse dung were 0.153 per cent and 0.175 per cent, respectively, values too small to allow mineralization of phosphorus. In 9 days the organic phosphorus in green fodder compost increased to 0.3 per cent, and a rapid release of phosphorus could be established. In horse dung compost the critical point was reached more slowly, although it seemed to be somewhat lower than in the green fodder compost, which contained plenty of very readily available carbohydrates. The organic phosphorus content of cattle manure was 0.221 per cent. It seemed to be sufficient to permit mineralization of phosphorus, although the process did not occur so rapidly as in the wheat bran compost with an organic phosphorus content of 0.780 per cent, or in the fungal material with 0.274 per cent organic phosphorus.

DISCUSSION

The experimental results reported clearly prove that a certain regularity exists in the biological absorption and mineralization of phosphorus in organic material undergoing decomposition. The assimilation of phosphorus is influenced by the nature of the carbon source, that is, its availability, or the rapidity with which the carbon compound can be consumed by normal microflora. In absence of a method for estimating the amount of this available carbon, elucidation of the entire problem of biological absorption of phosphorus is impossible. For practical purposes, however, it can be said that decomposition of natural organic material requires 0.1 to 0.4 per cent phosphorus for every unit of dry matter broken down. As an average value, 0.2 per cent phosphorus may be given.

This fact applied in practice explains certain phenomena. It has sometimes been recommended that, in preparing artificial manure from straw or other materials rich in carbohydrate, nitrogen and phosphorus be added in large quantities. But the manurial effect of such composts has proved to be less than was anticipated on the basis of the amount of phosphorus added (4). This is due, naturally, to the conversion of added inorganic phosphorus into organic compounds during humification, the process being continued in soil if the mineralization limit was not reached earlier.

In her previous publication (7) the author pointed out that undecomposed farm manure has no undesirable effect when added to soil if peat moss was used as litter. If the manure was collected with a large amount of straw litter, however, biological absorption of phosphorus may take place in the soil, because the organic phosphorus content of the dry matter may be below 0.2 per cent. In such a case the total amount of phosphorus is, in general, so large that the microbes need not assimilate soil phosphorus, but if material rich in carbon and poor in phosphorus is applied to soil, the microorganisms will compete with higher plants for available soil phosphorus. The same thing must be taken into consideration when the phosphorus fertilization of organic soils is in question. Probably the biological absorption of phosphorus by soil organisms at the expense of peat humus is not very effective in acid bog peat, but it may lead to competition for phosphorus in good swamp peat soils. Attention must be paid to the fact that in peat soils chemical and colloid-chemical absorption greatly decreases the amount of available phosphorus, thus intensifying competition for it. Some results obtained from analyses of soil samples of a field experiment on lowmoor peat (6, p. 64) evidently indicate that there is a considerable increase in the amount of organic phosphorus at the expense of annual dressings with phosphates. The amounts of organic phosphorus in the soil reported as P_2O_5 were as follows: first year, 890 ppm. or 46 per cent of total P_2O_5 ; fifth year, 1,020 ppm. or 56 per cent of total P_2O_5 ; tenth year 1,200 ppm. or 51 per cent of total P_2O_5 .

Because a comparatively significant relationship exists between the amount of phosphorus assimilated and the amount of organic material decomposed, there must be some tendency to a constant ratio between humus carbon and organic phosphorus in soil. According to the results obtained from analyses of 100 Finnish soil samples (6), the ratio total C/organic P ranges approximately from 100 to 150 in mineral soils. Accumulation of organic phosphorus in soil as complex compounds resistant to mineralization explains why this ratio can be as low as 100. For the peat soils investigated, an average value of about 700 was obtained. This indicates clearly the low degree of humification in peat soils.

SUMMARY

An attempt was made to elucidate the biological absorption of phosphorus in nature due to an abundant supply of energy-yielding material.

On the basis of theoretical calculations and experimental results it was concluded that, in general, the amount of phosphorus assimilated per unit of purified organic material, completely decomposed, falls within certain limits. For various organisms, these limits proved to be about 0.15 and 0.5 per cent of the amount of available organic compound in question. The average for mixed populations was given as 0.3 per cent P.

On this basis, the conclusion was drawn that during humification of natural organic matter no mineralization of organic phosphorus can be detected so long as the amount remains below a certain limit, which varies to some extent,

depending on the availability of the carbon compounds in the organic matter and the phosphorus accessible to microorganisms. On the average, this limit for organic phosphorus can be considered to be about 0.2 per cent of the dry matter.

Some phenomena arising from biological absorption of phosphorus in soil and in composts are explained on the basis of these results.

REFERENCES

- (1) CHANG, S. C. 1939 The transformation of phosphorus during the decomposition of plant materials. *Soil Sci.* 48: 85-99.
- (2) CHANG, S. C. 1940 Assimilation of phosphorus by a mixed soil population and by pure cultures of soil fungi. *Soil Sci.* 49: 197-210.
- (3) CHOUCHEK, M. 1929 La lutte entre les plantes cultivées et les microorganismes du sol pour leur nutrition minérale; action du sang desséché sur l'engrais phosphaté. *Compt. Rend. Acad. Sci.* [Paris] 189: 262-264.
- (4) CROWTHER, E. M. 1942 Straw on the land. *Jour. Min. Agr.* [Gt. Brit.] 49: 146-150.
- (5) DUSHECHKIN, A. I. 1911 The biological adsorption of phosphoric acid in the soil. *Zhur. Opytn. Agron.* 12: 650-668. (Abstract in *Exp. Sta. Rec.* 27: 216. 1912.)
- (6) KAILA, A. 1948 Viljelysmaan orgaanisesta fosforista [On the organic phosphorus in cultivated soils]. *Valt. Maatalouskoet. Julk.* 129.
- (7) KAILA, A. Karjanlannan fosforista [On phosphorus in farm manure]. *Maataloustiet. Aikak.* (In press).
- (8) LOCKETT, J. L. 1938 Nitrogen and phosphorus changes in the decomposition of rye and clover at different stages of growth. *Soil Sci.* 45: 13-24.
- (9) PAPADAKIS, J. S. 1947 Experiments on the immobilization of phosphorus. *Soil Sci.* 64: 365-369.
- (10) STOKLASA, J. 1911 Biochemische Kreislauf des Phosphations im Boden. *Centbl. Bakt.* (II) 29: 358-519.
- (11) TAM, R. K., AND MAGISTAD, O. C. 1936 Chemical changes during the decomposition of pineapple trash under field conditions. *Soil Sci.* 41: 315-327.
- (12) WAKSMAN, S. A. 1924 Influence of microorganisms upon the carbon-nitrogen ratio in the soil. *Jour. Agr. Sci.* 14: 555-562.

POTASSIUM STATUS AND AVAILABILITY TO CROPS OF NON-EXCHANGEABLE POTASSIUM IN SOME INDIAN RED AND LATERITE SOILS

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The red and laterite soils of India, which have developed under leaching conditions, are generally expected to be low in potassium. But contrary to expectation, some field experiments have failed to indicate any marked deficiency of available potassium for the crop. It was thought desirable, therefore, to investigate the forms in which potassium exists in these soils and the degree to which the different forms become available to crops.

To study the nature of soil potassium, methods have been devised for estimating the so-called "immediately available," "remotely available" or "reserve," and "unavailable" potassium in soil. These methods consist in extracting the soil with water or other solvents such as certain organic and mineral acids of varying strength and solutions of various salts (4, 26). The methods are purely arbitrary, and hence cannot be expected to give closely approximate results for the potassium available to different types of crops. They are of value, however, because they form a common basis for comparing the nature of potassium in different types of soils and give some idea of the potassium physically adsorbed by the exchange complex, that contained in the secondary minerals, and that existing in the primary minerals of the soil. There are a few biological methods (15, 16, 17, 24, 27) of determining available potassium. A faint relationship seems to exist between the values obtained by biological methods, particularly Neubauer's potassium value, and the exchangeable potassium in soils (8) or the citric-acid-soluble soil potassium (25). For the purpose of the present paper, however, attention is devoted to chemical methods; namely, extraction with hydrochloric, citric, and acetic acids.

✓ It is generally assumed (2, 13, 18) that most, if not all, of the potassium taken up by a crop comes from the exchangeable form. Many investigators (6, 7, 19, 21), however, hold the view that the plant can take up nonexchangeable potassium also. Lamb (11) and Bartholomew and Janssen (1) have reported that plants can reduce with difficulty the amount of exchangeable potassium in soil below 2.5 mgm. per 100 gm. At this stage the plant depends mainly on the nonexchangeable potassium for its nutrition. If the supply of potassium from the nonexchangeable form is inadequate, the response to fertilization may occur not only at this stage but also when the exchangeable potassium, as suggested by other workers (8, 14), falls below 15 to 20 mgm. per 100 gm. soil.

The present investigation is divided into three sections:

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Section I, in which the relation of the exchangeable, citric-acid-soluble, and hydrochloric-acid-soluble forms of potassium to one another and to other soil factors is discussed.

Section II, in which an attempt is made to obtain further information on the citric-acid-soluble potassium in relation to the exchangeable and nonexchangeable potassium in soil.

Section III, which records the effects of fertilizer treatments on the exchangeable, citric acid-soluble, and hydrochloric-acid-soluble forms of potassium and on the adsorption of nonexchangeable potassium by a crop (rice) in a red soil at Dacca.

TABLE 1

*Origin, depth of samples, and some properties of Indian red and laterite soils**

ORIGIN	SOIL NO.	DEPTH OF SAMPLING	CLAY	SATURATION CAPACITY	TOTAL EXCHANGEABLE BASES	EXCHANGEABLE CALCIUM
		<i>inches</i>	<i>per cent</i>	<i>me./100 gm.</i>	<i>me./100 gm.</i>	<i>me./100 gm.</i>
Dacca Farm, Bengal.	D.F.	0-6	—	4.31	2.05	1.17
Dacca, Bengal.	1p	0-6	20.8 ✓	5.60	2.61	1.43
Suri, Birbhum, Bengal (laterite profile)	4p	0-12	12.5	2.40	1.39	0.67
	5p	12-18	20.0	5.50	3.48	2.25
	6p	18-48	39.6	13.90	7.63	4.97
Suri, Birbhum, Bengal . . .	7p	>156	n.d.	10.90	9.89	5.13
Suri, Birbhum, Bengal. . . .	8p	>156	n.d.	5.30	3.79	2.07
Himayeth Sagar, Hyderabad, Deccan (red soil profile) . .	18p	0-3	16.7	6.00	5.46	4.38
	19p	3-18	38.1	15.50	10.04	7.46
	20p	18-48	10.9	13.90	10.96	7.94
Raipur, C.P.	33p	0-4	12.5	4.40	3.83	2.13
Cannanore, Malabar.	45p	0-15	23.9	4.10	3.50	2.40
Nilgiri Hills 3000 feet above sea level	53p	0-20	23.2	19.58	18.92	14.91
Nilgiri Hills 7000 feet above sea level (red soil profile). .	60p	12-36	24.3	3.21	2.73	0.31
	61p	36-54	25.7	3.31	1.61	0.39
	62p	54-72	9.6	5.21	2.58	0.34
Guntur, Madras.	67p	0-8	27.5 ✓	18.66	10.54 ✓	11.83
Trivandrum, Travancore. . .	70p	0-18	27.1	4.75	3.38	0.97
Cape Comorin.	73p	0-6	39.2	6.06	4.41	1.36
Shillong, Assam.	119p	0-6	—	—	—	—

* Data taken from the annual reports of the Dacca University Scheme of Research on Indian Laterite and Red Soils (1937-1939), partly financed by the Indian Council of Agricultural Research.

SOIL SAMPLES

Twenty samples of Indian red and laterite soils were selected from the main body of samples of such soils collected by the senior author. The laboratory numbers, description, some properties, and the sources of the soils are given in table 1.

SECTION I. EXCHANGEABLE, CITRIC-ACID-SOLUBLE, AND HCl-SOLUBLE POTASSIUM IN SOILS

Experimental

Exchangeable potassium was determined by leaching with 0.5*N* acetic acid; citric-acid-soluble, by shaking with 1 per cent citric acid for 24 hours; and hydro-

chloric-acid-soluble, by heating with concentrated HCl for 6 hours. The potassium was estimated by a modified volumetric cobaltinitrite method developed in this laboratory. Briefly the method is as follows:

The solution in which the potassium is to be determined is evaporated to a small volume (5 to 10 ml.) and acidified with a few drops of glacial acetic acid; 5 ml. sodium nitrite solution and 5 ml. cobalt acetate solution are then added in that order, the latter being added rapidly with constant stirring. The mixture containing the precipitate $K_2NaCo(NO_2)_6 \cdot H_2O$ is stirred frequently, evaporated to dryness on a water bath, cooled, extracted with water, and filtered through a sintered No. 4 crucible. The precipitate is washed with 0.005*N* nitric acid containing 2.5 per cent $Ca(NO_3)_2$. The precipitate and the crucible are then added to a measured excess of cold acidified potassium permanganate solution, which is heated to boiling. Excess of standard oxalic acid or sodium oxalate is added and back titrated with potassium permanganate. Potassium is calculated from the following equation: $K(\text{in mgm.}) = V \times N \times 7.1084$, where *V* represents the volume, in milliliters, of potassium permanganate required to oxidize the precipitate, and *N* represents the normality of potassium permanganate.

Results and discussion

Exchangeable potassium. Table 2 shows that the exchangeable potassium ranges from 1.56 mgm. in soil 62p (a subsoil) to 33.32 mgm. in soil 53p (a topsoil), the average value being 8.55. Stewart (25) found the exchangeable potassium in a number of Scottish soils to range from 3 to 47 mgm. per 100 gm. soil. with an average value of 11.3 mgm. The lower values for the Indian soils are to be expected in view of the prevailing leaching conditions leading to laterization in humid tropics.

As all the soils with the exception of 53p and 73p contain much less than 15 to 20 mgm. exchangeable potassium per 100 gm., they are likely to respond to potassium fertilizers (8, 14). Unfortunately, no information as to the response to potassium fertilization in the field is available for those soils. But soil D. F. (a red soil at Dacca, exchangeable potassium 6.35 mgm. per 100 gm.) has been subjected to potassium fertilization for 3 successive years with virtually no response. There may be two reasons for this: first, the soil, even with so little exchangeable potassium, may still be capable of supplying sufficient for the crop, and if this is so, the 15- to 20-mgm. limit affecting plant growth must be considerably modified for the red soils; or, second, the crop may obtain its potassium requirements from the nonexchangeable portion. Section II and III show that the crop may get a fair supply of potassium from the nonexchangeable portion.

The three sets of profile samples in table 2 show that in the laterite soil (Nos. 4p, 5p, 6p), the exchangeable potassium increases with depth; in one red soil (Nos. 18p, 19p, 20p) it decreases, and in the other (Nos. 60p, 61p, 62p) it is maximum in the intermediate zone. Although these results are inadequate for generalization, it appears that exchangeable potassium may increase in laterite soils with depth of the profile whereas the variation is irregular in the red soils.

Citric-acid-soluble potassium. Table 2 shows that the citric-acid-soluble potassium ranges from 1.38 to 30.36 mgm. per 100 gm soil, and averages 6.45 mgm.

In the soils studied by Stewart (25), the range is from 1 to 33.5 mgm. and the average 6.16. It may be noted here that though the content of exchangeable

TABLE 2
Exchangeable, citric-acid-soluble, and hydrochloric-acid-soluble potassium in soil

SOIL NO.	POTASSIUM					
	Exchangeable	Citric-acid-soluble	HCl-soluble	Citric-acid-soluble, % of exchangeable	Exchangeable, % of HCl-soluble	Citric-acid-soluble, % of HCl-soluble
	mgm./100 gm.	mgm./100 gm.	mgm./100 gm.			
D.F.	6.35	1.85	237	29.1	2.67	0.78
1p	4.47	2.62	335	58.6	1.33	0.78
4p	5.58	2.50	192	44.8	2.90	1.30
5p	6.39	4.51	258	70.9	2.47	1.74
6p	11.23	7.69	397	68.4	2.82	1.93
7p	5.25	2.86	343	54.4	1.53	0.83
8p	7.60	3.73	150	49.0	5.06	2.48
18p	9.87	6.39	150	64.7	6.58	4.26
19p	7.80	4.35	232	55.7	3.36	1.87
20p	6.34	4.83	174	76.3	3.64	2.78
33p	5.40	4.23	322	78.3	1.67	1.31
45p	8.92	6.23	185	69.8	4.82	3.36
53p	33.32	30.36	213	91.1	15.64	14.25
60p	3.20	3.26	199	101.8	1.10	1.63
61p	4.40	3.24	93	73.6	4.73	3.48
62p	1.56	1.38	29	88.4	5.37	4.75
67p	9.83	7.33	303	74.6	3.24	2.41
70p	8.22	5.77	103	70.2	7.98	5.60
73p	19.52	19.63	209	100.5	9.33	9.39
119p	5.82	6.31	503	108.4	1.15	1.25

potassium is low in the Indian soils studied, that of citric-acid-soluble potassium is similar to those of soils from Scotland and certain parts of Africa.

A close relationship is observed between the exchangeable and the citric-acid-soluble potassium in the Indian soils, the correlation coefficient being +.9782. A similar correlation, +.9786, was observed by Stewart for Scottish soils.

If all the citric-acid-soluble forms were merely a part of the exchangeable

potassium, one would expect that, with such a high correlation, the percentage of exchangeable potassium represented by the citric-acid-soluble fraction should be more or less constant. But that this is not so is evident from table 2, in which the range is shown to be from 29 to 108 per cent. It appears, therefore, that although the citric-acid-soluble portion comes largely from exchangeable potassium, thereby helping to maintain the high correlation, it also contains some nonexchangeable potassium. This is further evidenced by the fact that the percentage exceeds 100 in some soils. That citric acid does, in fact, bring into solution some of the nonexchangeable potassium is shown in Section II.

Hydrochloric-acid-soluble potassium. The HCl-soluble fraction is believed to be a measure of the soil's "reserve" potassium, which may in time become available to plants. In the soils studied, the amount ranges from 29 to 503 mgm. per 100 gm. and averages 242 mgm. (table 2). For a number of Scottish soils, the value ranges from 116 to 1,008 mgm. and averages 433.3. It is evident, therefore, that the red and laterite soils of India are poorer in "reserve" potassium than the soils of temperate humid regions.

The HCl-soluble potassium for all the soils taken together shows no relation to either the exchangeable or the citric-acid-soluble portion. The exchangeable ranges from 1.1 to 15.64 per cent and the citric-acid-soluble from 0.78 to 14.25 per cent of the HCl-soluble potassium.

As shown in table 3, the degree of potassium saturation in the soils ranges from 0.77 to 8.25 per cent with an average of 3.25, and the exchangeable potassium as percentage of the total exchangeable bases ranges from 1.3 to 11.3 with an average of 4.81. The exchangeable potassium in a number of Wooster silt loams was found to average, 4.16 per cent of the total exchangeable bases (23). According to Pierre and Scarseth (20) and Hoagland and Martin (9), these values have an important bearing on absorption of potassium from soil by plants. If the base-exchange complex contains a relatively high absolute amount, the rate of potassium absorption by plants will be high. Table 3 gives the ratios between exchangeable calcium and exchangeable potassium. Nostitz (18) expressed the belief that a certain ratio of Ca to K is best for normal growth of plants. Ehernberg (5), Lagatu and Maume (10), and Lipman, Blair, and Prince (12) showed a decreased absorption of potassium by plants due to liming. A relatively high concentration of calcium in the soil solution may retard the entrance of potassium to plants; therefore, a wide ratio of Ca to K (for example, 180) may lead to serious nutritional disturbances in plants (11). The figures for the Indian soils indicate that this ratio is not very high, the maximum being 49 and the average 17.23. So far as the laterite and red soils of India are concerned, therefore, potassium absorption by plants will not be retarded by the amounts of calcium generally present in these soils.

SECTION II. CITRIC-ACID-SOLUBLE IN RELATION TO EXCHANGEABLE AND NONEXCHANGEABLE POTASSIUM

That citric-acid-soluble potassium is generally less than exchangeable potassium is due to the nature of extraction from the soil. In citric-acid extrac-

tion the soil is shaken for a definite time until an equilibrium is reached in the solution in contact with the soil, whereas in determining the exchangeable potassium such equilibrium is continuously disturbed by successive leachings with fresh quantities of solvent until potassium in the extracts becomes vanishingly

TABLE 3

Degree of potassium saturation and relation of exchangeable potassium to exchangeable calcium and to total exchangeable bases in soils

SOIL NO.	Degree of K-SATURATION	$\frac{\text{EXCHANGEABLE Ca}}{\text{EXCHANGEABLE K}}$	EXCHANGEABLE K, % OF TOTAL EXCHANGEABLE BASES
	<i>per cent</i>		
D.F.	3.71	7.22	7.8
1p	2.03	12.54	4.3
4p	5.95	4.71	10.2
5p	2.96	13.80	4.6
6p	2.06	17.31	3.7
7p	1.23	38.28	1.3
8p	3.66	10.67	5.1
18p	4.21	17.31	4.6
19p	1.29	37.30	1.9
20p	1.17	49.01	1.5
33p	3.14	15.43	3.5
45p	5.56	10.52	6.5
53p	4.36	17.45	4.5
60p	2.24	3.78	3.0
61p	3.38	3.48	6.9
62p	0.77	8.50	1.5
67p	1.36	46.57	2.4
70p	4.42	4.61	6.2
73p	8.25	2.72	11.3

small. From his experiment, Stewart (25) concluded that citric-acid-soluble potassium comes only from the exchangeable form. The previous section, however, indicates that not all the citric-acid-soluble potassium in the soils examined consists of exchangeable potassium. Craig and Lincoln (3) also observed that in some soils the citric-acid-soluble form exceeded the exchangeable potassium. For this, they could give no explanation. In this section an attempt is made to gain further information on the citric-acid-soluble potassium.

Experimental

In eight of the twenty samples examined in the previous section, the following determinations were made:

1. Exchangeable potassium left after removal of the citric-acid-soluble portion.
2. Citric-acid-soluble potassium after removal of exchangeable potassium.
3. Citric-acid-soluble potassium in successive extractions,
4. Exchangeable potassium after fourth extraction with citric acid in determination 3.

In determinations 2 and 4, where the quantity of potassium is expected to be small, larger amounts of soils and larger aliquots of extractions were taken to minimize the experimental error. The results are given in tables 4 and 5.

TABLE 4

Exchangeable and nonexchangeable potassium extracted from soils by citric acid

SOIL NO	POTASSIUM PER 100 GM. SOIL					
	Exchangeable	Exchangeable after removal of citric-acid-soluble	Citric-acid-soluble	Citric-acid-soluble after removal of exchangeable	Exchangeable extracted by citric acid	
	(a)	(b)	(c)	(d)	(a - b)	(c - d)
	mgm.	mgm.	mgm.	mgm.	mgm.	mgm.
18p	9.87	3.70	6.39	0.46	6.17	5.93
45p	8.92	3.06	6.23	0.50	5.86	5.73
53p	33.30	6.70	30.36	3.63	26.60	26.73
60p	3.20	0.97	3.26	0.90	2.23	2.36
67p	9.80	5.73	7.33	2.84	4.07	4.49
70p	8.22	2.96	5.77	0.50	5.26	5.27
73p	19.50	2.33	19.63	2.70	17.17	16.93
119p	5.82	0.70	6.31	1.18	5.12	5.13

Table 4 shows that a considerable amount of exchangeable potassium is left after extraction with citric acid, even in soils 73p, 60p, and 119p where the citric-acid-soluble potassium is equal to or slightly more than the exchangeable potassium. This obviously indicates that the citric-acid extracts contain not only the exchangeable potassium but also potassium from "other sources" in the soil. For the sake of clarity, the other sources collectively may be defined as the nonexchangeable portion of soil potassium. Column (a - b) shows the exchangeable potassium extracted by citric acid; column (c), the citric-acid-soluble potassium; column (d), the nonexchangeable potassium that comes into solution when the soil is extracted with citric acid after having been freed of exchangeable potassium. Although on theoretical grounds this amount may not be strictly equal to that which will be extracted by citric acid from the nonexchangeable portion when the exchangeable potassium has not been removed from the soil, nevertheless, the difference is likely to be very small and, to all intents and purposes, it may be assumed that column (d) gives the amount of potassium that will be extracted by citric acid from the nonexchangeable portion even in the presence of the exchangeable portion. Therefore column

(c - d) gives the amount of exchangeable potassium extracted by citric acid, and the figures in this column should be equal to the corresponding figures in column (a - b). It will be found that this is so. Hence, we may conclude that the "available" potassium as obtained by citric acid extraction does not consist wholly of exchangeable potassium but also contains some of the nonexchangeable form. This gives us some idea of why some soils low in exchangeable potassium fail to respond to applications of potassium fertilizer. It may be argued that the crop takes up potassium from the soil solution, in which the concentration is maintained chiefly by the exchangeable potassium. Successive cropping reduces the exchangeable potassium to a low critical value, which may be different for different soils, when a very small amount of potassium from the exchange complex comes into the soil solution. At about this point the potassium coming from the nonexchangeable portion into the soil solution determines mainly the availability of potassium to plants. If a continuous supply

TABLE 5

Potassium in successive extractions of soil with citric acid, and exchangeable potassium after fourth extraction with citric acid

SOIL NO.	POTASSIUM PER 100 GM. SOIL									
	Citric-acid-soluble					Ex-change-able	Ex-change-able after 4th citric-acid extn. (b)	Citric-acid-soluble after removal of exchangeable (d)	(a - b)	(c - d × 4)
	1st Extn.	2nd Extn.	3rd Extn.	4th Extn.	Total					
	(c ₁)	(c ₂)	(c ₃)	(c ₄)	(c)					
	mgm.	mgm.	mgm.	mgm.	mgm.	mgm.	mgm.	mgm.	mgm.	mgm.
53p	30.36	4.60	4.33	4.26	43.55	33.3	3.66	3.63	29.64	29.03
67p	7.33	4.33	4.10	3.73	19.49	9.8	1.96	2.84	7.84	8.13
73p	19.63	3.60	3.66	3.30	30.19	19.5	tr.	2.70	19.50	19.39

of potassium to the soil solution is maintained from the nonexchangeable portion, potassium fertilization is not likely to have much effect.

Table 5 shows the potassium in each of four successive extractions with citric acid and the exchangeable potassium after the fourth extraction. The total amount of potassium obtained by four successive extractions with citric acid far exceeds the exchangeable potassium of the soil. An appreciable amount of exchangeable potassium may still be left in some soils even after the fourth extraction. Column (d) gives the amount of potassium that comes into solution from the nonexchangeable portion when extracted with citric acid. Let us assume that this amount comes into solution every time the soil is extracted with citric acid; namely, in c₁, c₂, c₃, and c₄, irrespective of the amount of exchangeable potassium in the soil. If this assumption is correct, the figures in column (c - d × 4) should be equal to the exchangeable potassium removed by the four extractions with citric acid. On the other hand, column (a - b), which is the difference between the exchangeable potassium originally present in the soil and that after the fourth citric-acid extractions, also gives

the amount of exchangeable potassium removed by the four citric-acid extractions. The corresponding figures in these two columns are in close agreement.

If citric-acid extractions represent the conditions governing the availability of nutrients to plants, the foregoing results indicate that the Indian red and laterite soils are capable of continuously releasing some potassium, though the amount may be small, from the nonexchangeable portion, so that in such soils even when the exchangeable potassium is brought to a low level by continuous cropping, the response to potassium fertilization will depend not on the amount of the exchangeable potassium present in the soil but on the extent to which the potassium from the nonexchangeable portion meets the requirement of the crop. This point does not seem to have received much attention from previous soil workers.

SECTION III. EFFECTS OF FERTILIZER TREATMENTS ON EXCHANGEABLE, CITRIC-ACID-SOLUBLE, AND HCl-SOLUBLE POTASSIUM AND ON ABSORPTION OF NONEXCHANGEABLE POTASSIUM BY CROPS IN DACCA RED SOIL

The previous section discussed the possibility of absorption of nonexchangeable potassium by crops in laterite and red soils of India. This section reports a study of the variation in exchangeable, citric-acid-soluble, and HCl-soluble potassium in a red soil consequent on certain fertilizer and manure treatments and, incidentally, an effort to obtain evidence of the absorption, if any, of the nonexchangeable potassium by the crop (rice) and the extent to which this absorption is influenced by fertilizer treatments in field experiments.

Experimental

Seven "mixed" soil samples from plots receiving different chemical fertilizers and cow dung for 3 successive years were chosen for the present work. The soils under the following seven treatments, each replicated five times in $\frac{1}{8}$ -acre plots, were examined:

1. C=Control.
2. N=(NH₄)₂SO₄, approximately 330 pounds per acre.
3. P=superphosphate, approximately 80 pounds per acre.
4. K=K₂SO₄, approximately 80 pounds per acre.
5. NPK=2 + 3 + 4.
6. F = Cowdung containing N, P, and K as in 2, 3, and 4.
7. NPKF= 5 + 6.

Equal amounts of composite soil samples, taken from four holes (0 to 6 inches) from each of the five similarly treated plots, were mixed together to give a "mixed" sample.

The exchangeable, citric-acid-soluble, and HCl-soluble potassium of these mixed samples were determined. Similar "mixed" samples of grain and straw at harvest, obtained from the differently treated plots by random sampling, were analyzed for potassium.

Before the results are discussed, certain drawbacks in the experiment should be pointed out. First, the amount of potassium added in the fertilizers and in

the dung and the period of application (3 years) were too small to reflect large changes in the different forms of soil potassium. Second, no soil samples from the plots before adoption of the scheme of fertilizing were available. This led to loss of considerable information and to difficulties in interpreting the results. Lastly, grain and straw at harvest were analyzed for only the fourth year; it is assumed that their composition at harvest was more or less the same in the previous years.

Results and discussion

Table 6 shows that both exchangeable and citric-acid-soluble potassium of all the treated plots are higher than those of the control and that they are maximum for the potassium-treated plots. The HCl-soluble potassium, on the other hand, may be regarded as equal for all the plots, the maximum variation

TABLE 6
*Exchangeable, citric-acid-soluble, and HCl-soluble potassium in a
Dacca red soil under different fertilizer treatments*

TREATMENTS*	POTASSIUM IN 100 GM. SOIL		
	Exchangeable	Citric-acid-soluble	HCl-soluble
	mgm.	mgm.	mgm.
C	6.35	1.85	237
N	7.65	2.45	238
P	7.55	2.48	240
K	9.02	3.34	229
NPK	8.78	2.00	239
F	7.75	2.24	236
NPKF	7.82	2.70	224

* See text for description of treatments.

± 4 per cent, being slightly more than the experimental error. In other words, the HCl-soluble potassium remains unaffected by fertilizers, at least at the rates applied.

The potassium content varies widely for both grain and straw from different plots (table 7). It is interesting that the percentage should be minimum for crops from the nitrogen-treated plot. Russell (22) made a similar observation. Furthermore, total uptake of potassium is also minimum in the nitrogen-treated plot. It seems, therefore, that nitrogen when applied alone retards the absorption of potassium. On the other hand, application of phosphorus stimulated the absorption of potassium, as seen from a comparison of the percentage as well as the total uptake of potassium in the crops from the control and the phosphorus-treated plots. Increased percentage of potassium in leaves of vines and tomatoes also was obtained by Russell (22) on application of phosphatic fertilizers.

Where potassium is added with manures, increased absorption of the element is to be expected because of its greater availability, as has been observed by Hoagland and Martin (9). This is fully reflected in the higher percentage of potassium in both grain and straw from the potassium-treated plots (K, NPK, F, and

NPKF) than in those from the control. Table 7 shows that the uptake of potassium exceeds the amount of added potassium in all cases. Table 8 shows the

TABLE 7

Potassium content of rice grain and straw, potassium added as fertilizer, and uptake of potassium by paddy in 3 years

TREATMENT*	POTASSIUM CONTENT		UPTAKE OF K IN 3 YEARS	K ADDED IN 3 YEARS
	Grain	Straw		
	%	%	lb./A.	lb./A.
C	.159	1.04	142	0
N	.133	1.01	131	0
P	.180	1.07	177	0
K	.184	1.36	185	88
NPK	.147	1.59	282	88
F	.179	1.02	162	88
NPKF	.179	1.36	268	176

* See text for description of treatments.

TABLE 8

Uptake of potassium by rice crop from nonexchangeable portion in soil in 3 years

TREATMENT*	UPTAKE OF K IN 3 YEARS	EXCESS OF K UPTAKE OVER THAT FROM CONTROL	EXCHANGEABLE K IN SOIL	EXCESS OF EXCHANGEABLE K OVER THAT IN CONTROL SOIL		NONEXCHANGEABLE K ABSORBED BY CROP IN EXCESS OF CONTROL (b + e)
	(a)	(b)	(c)	(d)	(e)	
	lb./A.	lb./A.	mgm./100 gm.	mgm./100 gm.	lb./A.	lb./A.
C	142	—	6.35	—	—	—
N	131	—11	7.67	1.32	26	15
P	177	35	7.55	1.20	24	59

* C = control; N = approximately 330 pounds $(\text{NH}_4)_2\text{SO}_4$ per acre; P = approximately 80 pounds superphosphate per acre.

TABLE 9

Uptake of potassium by rice crop from nonexchangeable form in soil in 3 years

TREATMENT*	K ADDED	EXCHANGEABLE K IN soil	EXCESS OF EXCHANGEABLE K OVER THAT IN CONTROL SOIL		BALANCE OF ADDED K FOR UPTAKE	ACTUAL UPTAKE OF K	
	(a)	(b)	(c)	(d)	(a - d)	(e)	[e - (a - d)]
	lb./A.	mgm./100 gm.	mgm./100 gm.	lb./A.	lb./A.	lb./A.	lb./A.
C	0	6.35	—	—	—	142	—
K	88	9.02	2.67	54	34	185	151
NPK	88	8.78	2.43	48	40	282	242
F	88	7.75	1.40	28	60	162	102
NPKF	176	7.82	1.47	29	147	268	121

* See text for description of treatments.

uptake of nonexchangeable potassium from phosphorus- and nitrogen-treated plots and table 9 the uptake of potassium from the K, NPK, F, and NPKF plots.

The previous section showed evidence that crops obtain their supply of potassium from both the exchangeable and the nonexchangeable forms in soil. As a result, the level of exchangeable potassium in a soil decreases in accordance with the absorption of such potassium by the crop. If, because of changed circumstances, the crop receives more potassium from the nonexchangeable form and therefore absorbs less of the exchangeable form, the change in the value of exchangeable potassium will be correspondingly less. In the experiment under investigation the exchangeable potassium in all the plots before fertilizers were applied may be assumed to have been equal. In the course of 3 years, the exchangeable potassium of the control plot decreased to 6.35 mgm. per 100 gm. soil (table 8). In the nitrogen-treated plot, it decreased to 7.67 mgm.; in other words, in this plot the crop absorbed $7.67 - 6.35$, or 1.32 mgm. per 100 gm. soil, that is, 26 pounds per acre of exchangeable potassium less than in the control plot. On the other hand, the total uptake of potassium by the crop on the nitrogen-treated plot was only 11 pounds per acre less than that of the control. The difference ($26 - 11 = 15$ pounds of K per acre) must have been absorbed from the nonexchangeable portion. This amount is obviously over and above any quantity that was absorbed by the crop of the control plot from the nonexchangeable potassium. Similarly, in the course of 3 years, the crop of the phosphorus-treated plot absorbed 24 pounds per acre of exchangeable potassium less than that absorbed by the crop of the control plot. On the other hand, the total uptake of potassium from the phosphorus-treated plot exceeded that from the control plot by 35 pounds per acre. Obviously then ($24 + 35$) 59 pounds of potassium per acre must have been absorbed by the crop from the nonexchangeable portion.

These results indicate that application of artificial nitrogenous and phosphatic fertilizers, possibly by stimulating microbial activity, renders a larger amount of nonexchangeable potassium available to the crop, and as a result less exchangeable potassium is absorbed.

If soluble potassium, as in the potassium-treated plots, is added, the crop will undoubtedly utilize this form and less of the exchangeable form already present. This is reflected in the higher values for exchangeable potassium in the potassium-treated plots than in the control (table 9). Column (d) shows the difference between the exchangeable potassium absorbed by the crop on the potassium-treated plots and that absorbed by the crop on the control plot. Column (a) gives the amount of potassium added as fertilizers in the potassium-treated plots. Column (a - d) represents the balance of added potassium available for uptake by the crop. Column (e) shows the actual uptake of potassium by the crop. The difference between the actual uptake and the balance available for uptake is given in column [e - (a - d)]. The difficulty in interpreting the results of this column arises from the fact that the original exchangeable potassium content of the soil is not known. In the control plot, 142 pounds of potassium was absorbed by the crop in 3 years. A considerable amount of this must have been absorbed from the nonexchangeable form, and even if the entire amount existed in the exchangeable form, still the crop on the NPK-

treated and K-treated plots absorbed at least 100 pounds (242 — 142) and 9 pounds (151 — 142) of potassium per acre respectively from the nonexchangeable form.

The results of the dung-treated plots in column [e — (a — d)] do not represent what actually happened in the soil. It will be seen that all the potassium of the added dung was assumed to be available to the crop at once. It is likely that a considerable amount of it was not in a soluble form. It is difficult, therefore, to say anything definite about the absorption or nonabsorption of potassium from the nonexchangeable form in these plots.

In view of the aforementioned defects of the experiment, the results obtained in this section may not be strictly accurate. Nevertheless, sufficient evidence appears to have been obtained of the absorption by the crop of non-exchangeable soil potassium, the amount of absorption being considerably influenced by the nature of the fertilizer and manure added.

SUMMARY

The exchangeable, citric-acid-soluble, and HCl-soluble forms of potassium in a number of Indian red and laterite soils were determined.

The amount of replaceable potassium in these soils is rather low, averaging about 8.55 mgm. per 100 gm. soil; in all but one or two soils, the exchangeable potassium is less than 15 to 20 mgm. per 100 gm.

The citric-acid-soluble potassium in the soils examined averages about 6.45 mgm. per 100 gm., and the amount is comparable to that in Scottish and African soils.

The HCl-soluble potassium in these soils averages about 240 mgm. per 100 gm., which is rather low in comparison with that in soils of temperate humid regions.

The exchangeable and the citric-acid-soluble forms of potassium in the soils examined show a correlation coefficient of +.9782.

The exchangeable potassium averages 4.8 per cent of the total exchangeable bases in these soils. That absorption of potassium by plants is not retarded by the amounts of calcium generally present in these soils is indicated.

An attempt was made to obtain information on the citric-acid-soluble potassium in relation to the exchangeable and nonexchangeable potassium of soil.

A considerable amount of exchangeable potassium is left in the soil after extraction with citric acid even in where the citric-acid-soluble potassium is equal to or slightly more than the exchangeable potassium; this indicates that citric acid brings into solution not only exchangeable potassium but also non-exchangeable.

The total amount of potassium in four successive extractions with citric acid far exceeds the amount of exchangeable potassium, and in some soils even after the fourth extraction an appreciable amount of exchangeable potassium may still be left in the soil.

Evidence is presented of extraction of a definite amount of potassium by citric acid from the nonexchangeable portion. This amount varies from soil to soil

but comes into solution every time the soil is extracted with citric acid, irrespective of the presence and the amount of the exchangeable potassium.

The effect of fertilizer treatment on exchangeable, citric-acid-soluble, and HCl-soluble potassium in a Dacca red soil was studied.

The exchangeable and the citric-acid-soluble forms of potassium in all the treated plots are higher than those of the control and are maximum for the potassium-treated plots.

Nitrogen applied alone retards, whereas phosphorus alone stimulates, absorption of potassium by the rice crop in the red soil at Dacca.

The application of nitrogenous and phosphatic fertilizers appears to make a larger amount of nonexchangeable potassium available to the crop.

Despite certain defects in the experiment, sufficient evidence appears to have been obtained of the absorption of potassium by the crop from the nonexchangeable portion in the soil, the absorption being considerably influenced by the nature of the fertilizer and manure added.

REFERENCES

- (1) BARTHOLOMEW, R. P., AND JANSSEN, G. 1931 The rate of adsorption of potassium by plants and its possible effect upon the amount of potassium remaining in soils from application of potassium fertilizers. *Ark. Agr. Exp. Sta. Bul.* 265.
- (2) BREAZEALE, J. F. 1928 Soil zeolites and plant growth. *Ariz. Agr. Exp. Sta. Tech. Bul.* 21: 199-520.
- (3) CRAIG, N., AND LINCOLN, R. 1928 The availability of potash in a typical Mauritius soil. *Jour. Agr. Sci.* 19: 397-403.
- (4) DYER, B. 1894 On the analytical determination of probably available mineral plant food in soils. *Trans. Jour. Chem. Soc.* 65: 115-167.
- (5) EHERNBERG, P. 1919 Das Kalk-Kali Gesetz. *Landw. Jahrb.* 54: 1-159.
- (6) FRAPS, G. S. 1929 Relation of the water-soluble potash, the replaceable, and acid-soluble potash to the potash removed by crops in pot experiment. *Tex. Agr. Exp. Sta. Bul.* 391.
- (7) GEDROIZ, K. K. 1931 Exchangeable cations of the soil and the plant: I. *Soil Sci.* 32: 51-63.
- (8) GISINGER, L. 1937 The influence of reaction on the solubility and availability of soil potash. *Forschungsdienst* 4: 314-323.
- (9) HOAGLAND, D. R., AND MARTIN, J. C. 1933 Adsorption of potassium by plants in relation to replaceable, nonreplaceable, and soil solution potassium. *Soil Sci.* 36: 1-32.
- (10) LAGATU, H., AND MAUME, L. 1928 Antagonisme du calcaire, a l'adsorption de la potasse par la vigne. *Comm. Cong. Internatl. du Vin et du Pin Maritime, Bordeaux.*
- (11) LAMB, J. 1935 The availability of soil potassium. *Soil Sci.* 40: 365-381.
- (12) LIPMAN, J. G., BLAIR, A. W., AND PRINCE, A. L. 1926 Effect of Lime and fertilisers on the potash content of soil and crop. *Internal. Rev. Sci. and Pract. Agr. [Rome]* 4: 546-553.
- (13) MAGISTAD, O. C. 1928 The hydrolysis of sodium and potassium zeolites with particular reference to potassium in the soil solution. *Ariz. Agr. Exp. Sta. Tech. Bul.* 22: 521-547.
- (14) MAGISTAD, O. C. 1934 Relation between replaceable potassium and field response to potash in Hawaiian soils. *Soil Sci.* 37: 99-103.
- (15) MEHLICH, A., TRUOG, E., AND FRED, E. B. 1933 The *Aspergillus niger* method of measuring available potassium in soil. *Soil Sci.* 35: 259-280.

- (16) MITSCHERLICH, E. A. 1925 Die Bestimmung des Düngerbedürfnisses des Bodens. Berlin.
- (17) NEUBAUER, H., AND SCHNEIDER, W. 1923 Die Nährstoffaufnahme der Keimpflanzen and ihre Anwendung auf die Bestimmung des Nährstoffgehalts der Böden. *Ztschr. Pflanzenernähr. u. Düngung*. 2,(A): 329-362.
- (18) NOSTITZ, A. von 1922 Über die Bedeutung des austauschbaren Bodenkaliums für die Pflanzenernährung. *Jour Landw.* 70: 45-72.
- ✓(19) ODELIEN, M. 1931 Potash in soils. *Tidsskr. Norske Landbr.* 38: 270-279.
- (20) PIERRE, W. H., AND SCARSETH, G. D. 1931 Determination of the percentage base saturation of soils and its value in different soils at definite pH values. *Soil Sci.* 31: 99-114.
- ✓(21) PROEBSTING, E. L. 1933 Adsorption of potassium by plants as affected by decreased exchangeable potassium in the soil. *Jour. Pomol. and Hort. Sci.* 11: 199-204.
- (22) RUSSELL, E. J. 1937 Soil Conditions and Plant Growth, ed. 7. Longmans, London.
- (23) SCHOLLENBERGER, C. J., AND DREIBELBIS, F. R. 1930 Effect of cropping with various fertilizer, manure, and lime treatments upon the exchangeable bases of plot soils. *Soil Sci.* 29: 371-394.
- (24) SMITH, A. M., AND DRYBUGH, A. 1934 The examination of soils by means of *Aspergillus niger*. *Trans. Jour. Soc. Chem. Indus.* 53: 250T-254T.
- (25) STEWART, R. 1929 The availability of the potassium in some Scottish soils. *Jour. Agr. Sci.* 19: 524-532.
- (26) TRUOG, E. 1930 The determination of the readily available phosphorus of soils. *Jour. Amer. Soc. Agron.* 22: 874-882.
- (27) WEISSMANN, H. 1927 Die Bestimmung des Nährstoffgehalts der Böden durch den Gefassversuch. *Ernähr. Pflanze* 23: 386-390.
- (28) WEISSMANN, H. 1928 Ein neues Verfahren zur Bestimmung des Nährstoffgehaltes der Böden durch den Gefassversuch. *Ernähr. Pflanze* 24: 30-31.

THEORY OF ION-EXCHANGE RELATIONSHIPS¹

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Numerous relationships have been proposed to describe the distribution at equilibrium of inorganic ions between the adsorbent and solvent phases of soil or clay systems. Some of these equations have been derived by analogy with expressions developed for the adsorption of gases on solids (1, 9, 11), some from special models of the clay surface (4), and others from considerations of the law of mass action (2, 5, 10).

In general, it can be said that none of the expressions developed thus far has proved very widely applicable. This fact is particularly disturbing, since soil chemistry is concerned with the distribution of ions between the particles and the soil solution, and unless soil chemistry is to remain essentially an empirical science a concerted attempt must be made to interpret its distinctive aspects such as ion exchange in terms of the fundamental laws of chemistry. In the present article an effort is made in this direction

A number of possibilities appear as reasons for the general inadequacy of ion-exchange relationships. One of these is obviously lack of equilibrium or the irreversibility of many ion-exchange processes in soils. Another possible reason is that many soils or clays may be mixtures of widely different types of minerals. A third reason may be that the theory used in developing the ion-distribution equation is faulty.

The present discussion concerns itself with the theory of ionic distribution as applied to mineralogically pure systems in which the ion-exchange process is at equilibrium and is completely reversible. The treatment is in terms of the partial free energies of the ions involved in the exchange process.

DEVELOPMENT OF THE GENERAL THEORY

In general, clay suspensions containing free electrolytes always can be separated into two phases which are in equilibrium with each other. The first of these (phase I) is the adsorbent phase and contains the adsorbed ions together with small but finite quantities of free electrolytes. The second phase (phase II) contains free electrolytes only.² For such a system of two phases the partial molal free energy of any free electrolyte must be the same in both phases at equilibrium. For example, let us consider a system of this kind which contains Na^+ and Ca^{++} in the adsorbed state and NaCl and CaCl_2 as free electrolytes. Then

$$(\bar{F}_{\text{NaCl}})_I = (\bar{F}_{\text{NaCl}})_{II} \quad (1)$$

$$(\bar{F}_{\text{CaCl}_2})_I = (\bar{F}_{\text{CaCl}_2})_{II} \quad (2)$$

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²Phase II does not contain appreciable amounts of the adsorbent particles because of the very low solubility of the adsorbent in water.

where \bar{F} is the partial molal free energy and the subscripts I and II refer to the adsorbent and aqueous phases.

The partial molal free energy of any electrolyte can be expressed formally as the sum of the partial molal free energies of the cation and anion of the electrolyte. That is, for an electrolyte BX_r ,

$$\bar{F}_{BX_r} = \bar{F}_{B^+} + r\bar{F}_{X^-}$$

Equations (1) and (2), therefore, can be written as follows

$$(\bar{F}_{Na^+} + \bar{F}_{Cl^-})_I = (\bar{F}_{Na^+} + \bar{F}_{Cl^-})_{II} \quad (3)$$

$$(\bar{F}_{Ca^{++}} + 2\bar{F}_{Cl^-})_I = (\bar{F}_{Ca^{++}} + 2\bar{F}_{Cl^-})_{II} \quad (4)$$

If \bar{F}_{Cl^-} is eliminated from equations (3) and (4) we obtain

$$(2\bar{F}_{Na^+} - \bar{F}_{Ca^{++}})_I = (2\bar{F}_{Na^+} - \bar{F}_{Ca^{++}})_{II} \quad (5)$$

Equation (5) is equivalent to the statement that the partial molal free energy of an ion in any phase is the same at equilibrium. As will be apparent later, this does not mean, however, that the concentration of the ion is necessarily the same in all of the phases.

In the general case, the partial molal free energies of the cations in phase I are contributed to both by the *cations associated with the adsorbent* and by those associated with the anions of the free electrolytes. In the present discussion we choose to consider a system in which the amounts of free electrolytes in phase I, although finite, are vanishingly small. In other words, the condition where the separation of adsorbent and solvent has been virtually complete is considered. This being the case, the contributions of the free cations in phase I can be neglected, and the partial molal free energies of the cations in this phase can be taken as referring to the adsorbed ions only. Equation (5) can thus be written

$$(2\bar{F}_{Na(ad)} - \bar{F}_{Ca(ad)})_I = (2\bar{F}_{Na^+} - \bar{F}_{Ca^{++}})_{II} \quad (6)$$

where $Na(ad)$ and $Ca(ad)$ refer to the ions in the adsorbed state.

The term $(2\bar{F}_{Na^+} - \bar{F}_{Ca^{++}})_{II}$ of equation (6) is a quantity that can be determined experimentally or can be evaluated on the basis of the principle of ionic strength. At low electrolyte concentrations, for which the ionic strength principle can be applied,

$$(2\bar{F}_{Na^+} - \bar{F}_{Ca^{++}})_{II} = RT \ln \frac{a^2(NaCl)}{a(CaCl_2)} = RT \ln \frac{m^2(NaCl)}{m(CaCl_2)} \cdot \frac{\gamma_{\pm^4}(NaCl)}{\gamma_{\pm^3}(CaCl_2)}$$

where m and γ_{\pm} refer to the molalities and the mean activity coefficients.

The term $(2\bar{F}_{Na(ad)} - \bar{F}_{Ca(ad)})_I$ of equation (6) can now be considered. This expression is not known theoretically, nor can it be measured. Some assumption has to be made to permit calculation of the free energy differences of ions in the adsorbed state. The nature of these assumptions can be made clear by an analysis of the individual quantities $\bar{F}_{Na(ad)}$ and $\bar{F}_{Ca(ad)}$. Such an analysis is outside the realm of thermodynamics because the individual partial molal free energies of

ions are not thermodynamically definable, although their differences and certain other linear combinations are rigorously definable. Nevertheless, we are justified in considering the extrathermodynamic significance of the individual terms $\bar{F}_{\text{Na}(ad)}$ and $\bar{F}_{\text{Ca}(ad)}$ in relation to the energy field on the surface, provided this treatment can be utilized to derive a significant expression for the difference, $(2\bar{F}_{\text{Na}(ad)} - \bar{F}_{\text{Ca}(ad)})_I$.

In general the partial molal free energy of any adsorbed ion, A , is dependent on the following variables: concentration, potential energy of the field, pressure (hydrostatic and osmotic), and temperature. That is

$$\bar{F}_A = \phi_1(C_A) + \phi_2(\xi) + \phi_3(P) + \phi_4(T).$$

In this treatment secondary effects due to the mutual influence of C upon ξ etc. are ignored. Such effects are, in general, of a smaller order of magnitude than the primary effect.

The potential energy function, $\phi_2(\xi)$, can be divided into two terms. The first of these, $\phi(\psi)$, represents the nonspecific interactions in which the ions are considered as point charges. The second term, $\phi(W)$, represents the potential energy due to mutual specific interactions between ions and to the specific interactions of ions with the charged complex as a result of the characteristic properties of the ions. Thus

$$\bar{F}_A = \phi_1(C_A) + \phi_2(\psi) + \phi_2(W) + \phi_3(P) + \phi_4(T)$$

Under conditions of constant pressure and temperature, $\phi_3(P)$ and $\phi_4(T)$ are constant and

$$\bar{F}_A = \phi_1(C_A) + \phi_2(\psi) + \phi_2(W) + \text{constant}$$

In the case of an exchange reaction, further simplification of the above equation can be made, because the total number of primary charges for a given amount of adsorbent is constant. That is, $\phi_2(\psi)$ is a constant and

$$\bar{F}_A = \phi_1(C_A) + \phi_2(W) + \text{constant}.$$

For the difference between the partial molal free energies of two adsorbed ions we can write

$$\bar{F}_A - \bar{F}_B = \Delta\phi(C) + \Delta\phi(W) \quad (7)$$

Ion-exchange equations as ordinarily written contain concentration terms only. That is, they are concerned solely with $\Delta\phi(C)$. It is important to realize that such a procedure is theoretically sound only if $\Delta\phi(W)$ is invariant for a given pair of ions. The present development will also proceed on the assumption that $\Delta\phi(W)$ is constant for any pair of ions.³ The significance of this assumption will be discussed in a later section.

On the assumption that $\Delta\phi(W)$ is a constant for a pair of ions, equation (7) reduces to

$$\bar{F}_A - \bar{F}_B = \Delta\phi(C) + \text{constant}$$

³A possible exception may be pairs involving H ion, because of the considerable evidence that in clays hydrogen is bound to the surface by covalent linkages as well as by electrovalent bonds.

and

$$(2\bar{F}_{\text{Na(ad)}} - \bar{F}_{\text{Ca(ad)}})_I = 2\phi(C_{\text{Na(ad)}}) - \phi(C_{\text{Ca(ad)}}) + \text{constant}.$$

The quantities $\phi(C_{\text{Na(ad)}})$ and $\phi(C_{\text{Ca(ad)}})$ can now be evaluated. To start, their form should be logarithmic to conform to the general thermodynamic procedure of writing the free energy as a logarithmic function of the activity; that is,

$$(2\bar{F}_{\text{Na(ad)}} - \bar{F}_{\text{Ca(ad)}}) = RT \ln \frac{\pi^2(C_{\text{Na(ad)}})}{\pi(C_{\text{Ca(ad)}})} + \text{constant}.$$

where $RT \ln \pi(C_{\text{Na(ad)}}) = \phi(C_{\text{Na(ad)}})$.

To summarize, the condition for equilibrium in the ionic exchange process under consideration is

$$(2\bar{F}_{\text{Na(ad)}} - \bar{F}_{\text{Ca(ad)}})_I = (2\bar{F}_{\text{Na}^+} - \bar{F}_{\text{Ca}^{++}})_{II}$$

or

$$RT \ln \frac{\pi^2(C_{\text{Na(ad)}})}{\pi(C_{\text{Ca(ad)}})} + \text{constant} = RT \ln \frac{m^2(\text{NaCl})}{m(\text{CaCl}_2)} \cdot \frac{\gamma_{\pm^4}(\text{NaCl})}{\gamma_{\pm^3}(\text{CaCl}_2)}.$$

or

$$\frac{\pi^2(C_{\text{Na(ad)}})}{m^2(\text{NaCl})} \cdot \frac{m(\text{CaCl}_2)}{\pi(C_{\text{Ca(ad)}})} \cdot \frac{\gamma_{\pm^3}(\text{CaCl}_2)}{\gamma_{\pm^4}(\text{NaCl})} = \text{constant}.$$

The above equations have been written for the distribution of Na and Ca ions between phases I and II. Such an equation can be developed for any pair of adsorbed ions A and B , the valencies of which are 1 and r respectively. Thus the most general ion-exchange equation is

$$\frac{\pi^r(C_A)}{\pi(C_B)} \cdot \frac{m(\text{BCl}_r)}{m^r(\text{ACl})} \cdot \frac{\gamma_{\pm^{r+1}}(\text{BCl}_r)}{\gamma_{\pm^{2r}}(\text{ACl})} = \text{constant} \quad (8)$$

The form and the absolute value of $\frac{\pi^r(C_A)}{\pi(C_B)}$ will vary with the hypothesis used in developing the exchange equation. Some of the hypotheses that have been put forward will now be examined, and the value of $\frac{\pi^r(C_A)}{\pi(C_B)}$ will be obtained in each case.

EVALUATION OF THE π FUNCTIONS IN THE GENERAL EQUATION

It is evident that in the calculation of the *ratios* characteristic of an ion-exchange equation, the π functions can be regarded as the "active masses" of the adsorbed ions.

In the base-exchange equation proposed by Kerr (5) it is assumed that the active masses of the adsorbed ions are determined simply by their amounts. This hypothesis is equivalent to the assumption that the adsorbed ions A and B form, with the adsorbent, the compounds $A(X)$ and $B(X)$, which exist as two independent entities, and that the internal energy and degrees of freedom of the particles of each type are not influenced by the relative concentration of the types.

In other words, it is assumed that $A(X)$ and $B(X)$ can be treated as pure phases and

$$\frac{\pi^r(C_A)}{\pi(C_B)} = \frac{C_A^r}{C_B}$$

This hypothesis is inadequate because association of any particular adsorption site with any particular ion is impossible. Moreover, there would always exist a possibility for additional increase in entropy due to mixing and the system could not be considered to have attained equilibrium.

Vanselow (10) has proposed an ion-exchange equation which rests upon the assumption that the "activity of an adsorbed ion" is equal to its mole fraction in the adsorbent phase. This assumption has been given further consideration by Kielland (6) and by Boyd *et al.* (1). That is

$$(C_A) = \frac{C_A}{C_A + C_B + C_C + C_D \dots}$$

where the amounts of the adsorbed ions C_A , C_B , etc., are expressed in moles and the series in the denominator includes all of the ions in the adsorbent phase. On this assumption,

$$\frac{\pi^r(C_A)}{\pi(C_B)} = \frac{C_A^r}{C_B(C_A + C_B + C_C + C_D \dots)^{r-1}}$$

Vanselow proposes this hypothesis by analogy with perfect mixed systems that obey Raoult's law. That is, the adsorbed ions A and B are considered to form, with the adsorbent, complexes $A(X)$ and $B(X)$ which exist in the form of ideal "mixed crystals."

It is important to realize that Raoult's law was developed for mixed systems not possessing any characteristic lattice properties. In the application of Raoult's law to ion-exchange equilibria, therefore, the lattice properties of the adsorbent are deliberately ignored.

Moreover, in terms of statistical mechanics, Vanselow's hypothesis states that a divalent ion such as Ca^{++} can occupy any two adsorption sites. *There is no restriction placed on the sites; they may or may not be far separated.* It is only under these conditions that complete randomness, equivalent to the mole fraction hypothesis, is obtained. In light of these considerations it seems quite likely that Vanselow's formulation may be an oversimplification of the problem.

Guggenheim (3) has proposed a theory for the adsorption of gases on surfaces in which a gas molecule can occupy more than one adsorption site. This theory has been adopted by Krishnamoorthy, Davis, and Overstreet (7) for the case of ion adsorption on clays and other ion-exchange materials. In its modified form, the theory states that the active mass of an adsorbed ion A is proportional to

$$q_A C_A + q_B C_B + q_C C_C + \dots$$

in which C_A , C_B , etc., are the amounts of the ions present in the adsorbed state

expressed in moles and q_A , q_B , etc., are parameters dependent on the valency of the ions and the lattice properties of the adsorbent. That is

$$\pi(C_A) = \frac{C_A}{q_A C_A + q_B C_B + q_C C_C + \dots},$$

and

$$\pi(C_B) = \frac{C_B}{q_A C_A + q_B C_B + q_C C_C + \dots},$$

and

$$\frac{\pi^r(C_A)}{\pi(C_B)} = \frac{C_A^r}{C_B(q_A C_A + q_B C_B + q_C C_C + \dots)^{r-1}}$$

The advantage of this hypothesis lies in the fact that it takes into account explicitly the lattice properties of the adsorbent. The theory deals with a term, Z , which is equal to the number of adsorption sites adjacent to a given adsorption site. The parameter q mentioned above is defined by the theory in terms of Z and the valency of the adsorbed ion r ; that is, $qZ = rZ - 2r + 2$.

For the case of clays and synthetic resins it is reasonable to consider the distribution of adsorbed ions as a surface array and assign Z the value 4. On this assumption $q_A = \frac{r_A + 1}{2}$. From this it follows that the parameter q has the value 1 for monovalent ions, $1\frac{1}{2}$ for divalent ions, and 2 for trivalent ions.

It might be mentioned that if the distribution of ions on the surface is considered to be a linear array, $Z = 2$ and $q = 1$ for any ion. Under these conditions the equation based on Guggenheim's theory becomes identical with the equation based on Vanselow's hypothesis although the hypothetical bases for the equation are different in the two cases.

In contrast to Vanselow's hypothesis, Guggenheim's theory asserts that if a divalent ion such as Ca^{++} is to be adsorbed, two adsorption sites are required and these sites should be adjacent. In other words, so far as Ca^{++} is concerned *the sites are located in groups of two*.

From the foregoing considerations it appears that the hypothesis concerning the π functions of adsorbed ions based on statistical thermodynamic considerations is the most reasonable. If this theory is accepted, the complete ion-exchange formulation is as follows. For a system containing in the aqueous and adsorbent phases the ionic species A , B , C , $D \dots$ of valencies r_A , r_B , r_C , \dots , the equilibrium for the exchange reaction of any pair, say A and B , is given by the expression

$$\frac{(C_A)^{r_B}}{(C_B)^{r_A}} \cdot (q_A C_A + q_B C_B + q_C C_C + \dots)^{r_A - r_B} \cdot \frac{(a_B)^{r_A}}{(a_A)^{r_B}} = K_{A,B} \quad (9)$$

where C_A , C_B , etc., refer to amounts in moles of the adsorbed ions and $q = \frac{r_i + 1}{2}$ for the assumption that each site on the adsorbing surface has four neighboring sites. The quantities a_A and a_B are the ionic activities in the aqueous phase and are evaluated as described earlier.

FURTHER COMMENTS ON THE TERM $\Delta\phi(W)$

It is instructive to consider further the significance of the assumption that $\Delta\phi(W)$ is a constant. For this purpose let us consider again the expression for the partial molal free energy of an adsorbed ion A at constant temperature and pressure:

$$\bar{F}_A = \phi_1(C_A) + \phi(W_A) + \text{constant}$$

As pointed out earlier, W_A represents those specific and characteristic interactions of the ion A with the adsorbent, molecules of the solvent phase, other ions of the system, etc. Thus W_A conceivably might vary with the ion, the nature of the adsorbent surface, and the medium in which the exchange process is carried out, including the amounts of other ions present.

Both $\phi_1(C_A)$ and $\phi_2(W_A)$ of the above equation may be expressed as logarithmic functions, and

$$\bar{F}_A = RT \log \pi(C_A) \cdot \gamma(W_A) + \text{constant}$$

where $RT \log \pi(C_A) = \phi_1(C_A)$ and $RT \log \gamma(W_A) = \phi_2(W_A)$.

On this basis the ion-exchange equation for any pair of ions A and B of valency 1 and r is

$$\frac{\pi'(C_A) \cdot \gamma'(W_A)}{\pi(C_B) \cdot \gamma(W_B)} \cdot \frac{(a_B)}{(a_A)^r} = k \quad (10)$$

where a_A and a_B are the activities in the aqueous phase.

It is evident from equation (10) that the activity of an ion in the adsorbed state is $\pi(C_A) \cdot \gamma(W_A)$. The function $\gamma(W_A)$, which does not contain any concentration terms, is equivalent to the activity coefficient of the adsorbed ion, A . From the foregoing development it is also evident that the assumption that $\Delta\phi(W)$ is constant is equivalent to the assumption that the activity coefficient ratio $\frac{\gamma'(W_A)}{\gamma(W_B)}$ is a constant.

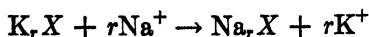
In light of our present knowledge there is no theory by which we can judge the validity of these assumptions. Justification for them can only be established by experiment. It should be emphasized, however, that the assumptions affect all the ion-exchange equations that have been proposed, since they deal with concentrations of the adsorbed ions only. For example, in the model proposed by Jenny (4), the assumptions concerning $\Delta\phi(W)$ are equivalent to the statement that the ratio of the "oscillation volumes" of two ions is a constant.

COMMENTS CONCERNING THE "VALENCY" OF THE ADSORBENT

A point of considerable interest is the question of the proper valency to be assigned to the adsorbent. Vanselow (10) indicated that the form of the exchange equation depends on the "valency" (basicity) of the adsorbent. He experimentally "proved" that, to obtain a satisfactory exchange constant, it is necessary to regard clays as being monobasic. However, we know from the structural properties of clays that a single particle may carry many thousands of adsorption

sites. In light of this knowledge, Vanselow's "proof" amounts to saying that an individual site is monobasic.

The theory presented in this paper has the advantage of being free from any necessary assumption regarding the valency of an adsorbent. For example, if the adsorbent is assumed to be an anion X of valency r , the reaction can be written



and

$$\frac{a_{K_r X}}{a_{Na_r X}} \cdot \left(\frac{a_{Na^+}}{a_{K^+}} \right)^r = k$$

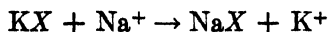
However $a_{K_r X} = a_{K(ad)}^r \cdot a_{X^-}$ and $a_{Na_r X} = a_{Na(ad)}^r \cdot a_{X^-}$.
Therefore:

$$\frac{a_{K(ad)}^r \cdot a_{X^-}}{a_{Na(ad)}^r \cdot a_{X^-}} \cdot \left(\frac{a_{Na^+}}{a_{K^+}} \right)^r = k$$

or

$$\frac{a_{K(ad)}}{a_{Na(ad)}} \cdot \frac{a_{Na^+}}{a_{K^+}} = k'.$$

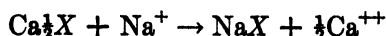
This equation is identical with the one that would have been obtained had the adsorbent been assumed to be monobasic and the reaction written as



It is thus immaterial what "valency" is assumed for the adsorbent, since this expression for the exchange constant will be identical in all cases.

THE ION-EXCHANGE EQUATION OF GAPON

In some quarters (8) considerable prominence has been given to an ion-exchange equation developed by Gapon (2). Gapon's formulation is consistent with the following expression for the exchange reaction between Ca^{++} and Na^+ :



That is,

$$\frac{(NaX)(Ca^{++})^{\frac{1}{2}}}{(Ca\frac{1}{2}X)(Na^+)} = k$$

The quantities in parentheses signify amounts and are expressed as milliequivalents for the adsorbed ions and as millimols for the solution ions.

All that can be said about Gapon's formulation is that it appears to be in conflict with the theory presented in this paper.

REFERENCES

- (1) BOYD, G. E., SCHUBERT, J., AND ADAMSON, A. W. 1947 The exchange adsorption of ions from aqueous solutions by organic zeolites: I. *Jour. Amer. Chem. Soc.* 69: 2818-2829.

- (2) GAPON, E. N. 1933 Theory of exchange adsorption in soils: *J. Gen. Chem. (U.S.S.R.)* 3(2):144-152.
- (3) GUGGENHEIM, E. A. 1944 Statistical thermodynamics of mixtures with zero energy of mixing. *Proc. Roy. Soc. [London] (A)* 183: 203-213.
- (4) JENNY, H. 1936 Simple kinetic theory of ionic exchange: I. *Jour. Phys. Chem.* 40: 501-517.
- (5) KERR, H. W. 1928 The identification and composition of the soil aluminosilicate active in base exchange and soil acidity. *Soil Sci.* 26: 385-398.
- (6) KIELLAND, J. 1935 Thermodynamics of base-exchange equilibria of some different kinds of clays. *Jour. Soc. Chem. Indus.* 54: 232T-234T.
- (7) KRISHNAMOORTHY, C., DAVIS, L. E., AND OVERSTREET, R. 1948 Ionic exchange equations, derived from statistical thermodynamics. *Science* 108: 439-440.
- (8) MAGISTAD, O. C., FIREMAN, M. AND MABRY, B. 1941 Comparison of base exchange equations founded on the law of mass action. *Soil Sci.* 57: 371-379.
- (9) VAGELER, P., AND WOLTERS DORF, J. 1930 Beiträge zur Frage des Basenaustausches und der Oziditäten. *Ztschr. Pflanzenernähr., Düngung, u. Bodenk. (A)* 15: 329-342.
- (10) VANSELOW, A. P. 1932 Equilibria of the base-exchange reaction of bentonites, permutites, soil colloids, and zeolites. *Soil Sci.* 33: 95-113.
- (11) WIEGNER, G., AND JENNY, H. 1927 Über Basenaustausch an Permutiten. *Kolloid Ztschr.* 43: 268-272.

COMPOSITION OF WHITE OAK LEAVES IN ILLINOIS AS INFLUENCED BY SOIL TYPE AND SOIL COMPOSITION

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The importance of vegetation in the development of soils has been widely recognized. It was the purpose of this investigation to determine whether soil type or soil composition influences the composition of white oak leaves. Results of a preliminary study of the influence of the position of the leaves on the tree and the date of sampling on leaf composition are also reported.²

MATERIALS AND METHODS

Field methods

Leaf sampling. Before leaf samples were collected to determine what, if any, influence soil differences had on leaf composition, it was necessary to know whether position had any influence on leaf composition. Accordingly, samples, each consisting of 300 leaves from each of six white oak trees, three growing on a deep loess soil and three on a strongly leached planosol developed from shallow loess over Illinoian till in the same county, were collected for the preliminary study. Besides the samples taken in late May, mid-July, and mid-September 1939, an additional set was taken in November to determine seasonal trends in leaf composition. In the second and third year of the study, samples consisting of 300 leaves from each of three white oak trees growing on each of ten soil sites in various parts of Illinois were collected on the dates indicated in the tables.

By varying the date of sampling from south to north, allowance was made for differences in beginning of the growing season; thus leaves of comparable physiological age were taken in every instance.

Care was exercised to obtain leaves from comparable exposures on the trees. Each leaf sample was oven-dried, ground in a hammer mill, weighed, and stored in mason jars under airtight conditions until chemical analyses could be made.

Soil sampling. At each site from which leaf samples were collected in 1940 and 1941, a pit was dug for sampling the soil profile. In the summer of 1948 samples of the A and B horizons of the same soils were collected with a soil auger for laboratory study. Each soil profile was studied. In the following descriptions, soil colors are indicated by Munsell notations:

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² Since the completion of this study, the text "Forest Soils" by Lutz and Chandler has been published. The reader is referred to chapters 6 and 10 for a review of pertinent literature.

Ava silt loam—Fayette County, Richland County.

Gray-brown podzolic soil developed from shallow loess over leached Illinoian till.

Slope 5-6.5 per cent.

A₁—0-4 inches. 10 YR 4.5/3 (moist) silt loam. Weak crumb structure.

A₂—4-10 inches. 10 YR 5/3 (moist) silt loam. Weak crumb structure.

A₃—10-17 inches. 7.5 YR 6/6-5/6 (moist) heavy silt loam. Coarse granular structure.

B₁—17-22 inches. 7.5 YR 5/6 (moist); some grayer coatings; silty clay loam. Blocky structure.

B₂—22-29 inches. 7.5 YR 6/6 to 10 YR 6/6 (moist) silty clay loam. Blocky structure.

B₃—29-37 inches. Slightly mottled to 10 YR 9/3-7.5 YR 5/8 (moist); some heavy 10 YR 7/3 coatings; silty clay loam with frequent sand grains. Blocky structure.

C—37 inches. 10 YR 6/4 to 7.5 YR 5/8 (moist) silty clay loam with more frequent sand grains than above.

Ava silt loam—immature phase—Wabash County, St. Clair County.

Gray-brown podzolic soil developed from deep loess over Illinoian till. Slope 5½-7 per cent.

A₁—0-4 inches. 10 YR 4/3 (moist) silt loam. Fine crumb to single grain structure.

A₂—4-11 inches. 10 YR 5/3-5/6 (moist), some organic staining, silt loam. Weak crumb structure.

A₃—11-17 inches. 10 YR 5/3-5/6 (moist) silty clay loam. Coarse granular structure.

B₁—17-22 inches. 10 YR 5/6 (moist) 10 YR 8/3 coatings; light silty clay loam. Muciform structure.

B₂—22-33 inches. mottled 10 YR 7/3-6/6-6/8 (moist) heavy silty clay loam. Blocky structure.

C—33-49 inches. 10 YR 6/6 to 7.5 YR 5/8 (slightly moist) silty clay loam. Subangular blocky structure.

Bluford silt loam—Richland County.

Light colored, strongly leached planosol developed from shallow loess over Illinoian till.

Slope approximately 1 per cent.

A₁—0-2 inches. 10 YR 4.5/2.5 (moist) silt loam. Single grain structure.

A₂—2-10 inches. 10 YR 5/3 (moist) silt loam. Granular to subangular.

A₃—10-18 inches. 10 YR 5/4-5/6 (moist) silt loam. Subangular structure.

B₁—18-24 inches. 10 YR 6/6-7/3 (moist) 10 YR 7/3 coatings; silty clay loam. Roughly prismatic to angular structure.

B₂—24-28 inches. 10 YR 6/6-6/3-6/8 (moist) 10 YR 7/3 coatings; silty clay loam. Blocky structure with some prismatic arrangement of aggregates.

B₃—28-36 inches. 10 YR 7/6 10 YR 8/2 7.5 YR 5/8 2.5 Y 6/2 coatings. Mottled heavy silty clay loam. Blocky structure with some prismatic arrangement of aggregates.

B₄—36 inches. Mottled 10 YR 7/2-7/6-4/3 light silty clay loam containing more sand than above.

Bluford silt loam—immature phase—St. Clair County.

Leached light colored gray-brown podzolic soil developed from moderately deep loess over Illinoian till. Slope 1 to 1½ per cent but breaks sharply to an 11 per cent slope into a drainage leading northeast.

A₁—0-4 inches. 2.5 Y 4/2 (moist) silt loam. Weak crumb structure.

A₂—4-16 inches. 10 YR 5/3-6/4 (moist) silt loam. Occasional iron pellets.

B₁—16-21 inches. 10 YR 6/6 (moist) 10 YR 7/3 coatings; silty clay loam. A few very small iron pellets. Subangular structure.

B₂—21-36 inches. 10 YR 5/6-6/4 (moist) 10 YR 7/3 coatings; silty clay loam. Angular structure.

C—36-48 inches. 10 YR 6/6 (moist) 10 YR 6/3 coatings; silty clay loam with brown mottling.

Deep boring at site showed a poorly to intermediately drained profile mottled throughout.

Clement silt loam—immature phase—Wabash County.

Gray-brown podzolic soil developed from deep loess over Illinoian till. Slope 7-20 per cent.

A₁—0-1 inch. 2.5 Y 3/2 (moist) silt loam. Weak crumb structure.

A₂—1-6 inches. 10 YR 6/4 (moist) silt loam.

A₃—6-9 inches. 10 YR 6/6 (moist) heavy silt loam. Subangular structure.

B₁—9-24 inches. 10 YR 6/6-5/6 (moist); some 10 YR 7/3 coatings; silty clay loam. Subangular structure.

B₂—24-38 inches. 10 YR 5/6-8/3-7/6-5/8-3/2-2/3 (moist) silty clay loam. Massive structure.

C₁—38-42 inches. 2.5 Y 7/4 (dry) 10 YR 5/8-6/8-2/2 (dry) silt loam. No pebbles observed. A horizon varied from 6-11 inches under this tree.

B horizon varied from 28-38 inches under this tree.

Clinton silt loam—Logan County, Ogle County, Marshall County.

Gray-brown podzolic soil developed from moderately deep loess over Wisconsin till in Logan and Marshall counties and over Illinoian till in Ogle County. Slope 4-5 per cent.

A₁—0-3 inches. 10 YR 5/1-5/2 (slightly moist) silt loam. Weak crumb structure.

A₂—3-11 inches. 10 YR 5/2-6/3 (slightly moist) silt loam. Weak crumb to medium grained

A₃—11-15 inches. 10 YR 6/3-6/4 (slightly moist); some 10 YR 7/2 coatings; heavy silt loam. Medium blocky structure.

B₁—15-26 inches. 10 YR 6/4-5/6 (slightly moist); some 10 YR 7/2 coatings; silty clay loam. Medium blocky structure.

B₂—26-36 inches. Mottled (10 YR 7/6 to 5/4) (7.5 YR 5/8) (2.5 Y 7/6) silty clay loam. Blocky structure.

Loess thicker than 58 inches in these areas.

After reaching air-dryness in the laboratory, each sample was weighed, divided into a major crushed portion and a minor portion, ground to 100-mesh size, and stored in glass containers for laboratory analysis.

Laboratory methods

Leaf material. All determinations were made in duplicate on 1-gm. samples, and all percentages were reported on a moisture-free basis.

1. Total N was determined by official A.O.A.C. method.
2. Potassium was precipitated as cobaltinitrite and determined volumetrically by oxidation in ceric nitrate and back titrated with sodium oxalate by unpublished method of DeTurk and Whyte.
3. Calcium was precipitated as the oxalate and titrated against standard ceric nitrate.
4. Magnesium was determined by the pyrophosphate method.
5. Phosphorus was determined by the standard molybdate method.

Soils. All determinations were made in duplicate on 10-gm. samples.

1. Adsorbed and acid-soluble phosphorus were determined by Bray's quick test on ground 100-mesh samples (2).
2. The pH was determined by use of a Beckman glass electrode.
3. Base-exchange capacity and total bases were determined on unground samples by method of Bray and Wilhite for determination of total replaceable bases in soils.
4. Replaceable Ca was precipitated as the oxalate and titrated against ceric nitrate. nitro-orthophenanthroline ferrous sulfate, being used as an indicator.
5. Replaceable Mg was determined by the Oxime (8-hydroxy quinoline) method.

DISCUSSION AND INTERPRETATION OF RESULTS

Seasonal trends in chemical composition of leaves

The seasonal trends in leaf composition are shown in tables 1 and 2. No significant differences in the chemical composition of the leaves from the bottom, middle, and topmost parts of the crowns of white oak trees could be detected (table 1). The concentrations of the various bases in the leaves fluctuated during the growing

TABLE 1

Seasonal variations in chemical composition of white oak leaves in 1939

Results in percentages, calculated on moisture-free basis

TREE DESIGNATION	MOISTURE			NITROGEN			PHOSPHORUS			POTASSIUM			CALCIUM			MAGNESIUM		
	May	July	Sept.	May	July	Sept.	May	July	Sept.	May	July	Sept.	May	July	Sept.	May	July	Sept.
<i>Immature Clement silt loam—Wabash County—southeastern Illinois</i>																		
X Blaze 1 Top....	4.78	8.04	6.12	2.54	2.12	2.16	.201	.166	.192	1.43	1.25	0.899						
X Blaze 1 Mid....	5.02	7.86	4.62	2.54	2.13	2.15	.206	.178	.209	1.33	1.14	1.04						
X Blaze 1 Bot ...	5.20	7.88	5.47	2.60	2.18	2.18	—	.173	.210	1.28	1.12	0.839						
Average..	—	—	—	2.56	2.14	2.16	.203	.172	.204	1.34	1.17	0.926						
<i>Immature Ava silt loam—Wabash County—southeastern Illinois</i>																		
X Blaze 2 Top....	3.52	8.07	6.09	2.20	1.83	1.96	.201	.167	.196	1.35	1.16	0.889						
X Blaze 2 Mid....	4.25	8.01	5.15	2.15	1.75	1.90	.202	.163	.190	1.35	1.27	1.05						
X Blaze 2 Bot ...	4.12	7.87	5.21	2.15	1.82	1.92	.204	.167	.189	1.39	1.18	0.998						
X Blaze 3 Top....	3.68	8.45	5.06	2.24	2.05	2.02	.205	.168	.179	1.36	1.22	1.04	0.98	1.11	1.41	.222	.243	.232
X Blaze 3 Mid....	4.63	8.40	6.13	2.25	2.01	2.05	.205	.171	.196	1.43	1.28	1.00	1.01	1.09	1.39	.226	.245	.234
X Blaze 3 Bot....	4.71	9.23	5.73	2.19	2.02	1.92	.208	.175	.197	1.36	1.23	1.07	1.02	1.12	1.36	.229	.239	.227
Average ..	—	—	—	2.32	2.00	2.03	.204	.170	.195	1.35	1.25	0.981	1.00	1.11	1.39	.226	.242	.231
<i>Clement silt loam—Wabash County—southeastern Illinois</i>																		
Y Blaze 1 Top....	3.36	7.62	4.05	2.12	1.86	2.03	.184	.142	.150	1.04	0.852	0.772						
Y Blaze 1 Mid....	2.97	8.86	6.14	2.16	1.91	2.01	.198	.131	.163	1.06	0.741	0.682						
Y Blaze 1 Bot ...	4.15	8.59	5.21	2.14	1.95	2.12	.196	.135	.166	1.16	0.889	0.764						
Y Blaze 2 Top... ..	4.79	10.30	4.52	2.05	1.93	2.12	.189	.140	.167	1.06	0.832	0.745						
Y Blaze 2 Mid....	3.54	14.36	6.02	2.16	2.13	2.09	.185	.131	.167	1.06	0.864	0.814						
Y Blaze 2 Bot ...	4.25	10.18	7.02	2.23	2.11	2.09	.188	.130	.168	1.07	0.785	0.803						
Y Blaze 3 Top....	4.27	10.45	4.54	2.18	2.12	2.10	.192	.140	.152	1.05	0.852	0.741	0.685	0.996	1.005	.213	.237	.213
Y Blaze 3 Mid....	3.66	10.68	5.02	2.11	1.93	2.12	.192	.139	.153	1.05	0.887	0.752	1.10	1.107	1.143	.220	.238	.213
Y Blaze 3 Bot....	4.96	7.57	6.17	2.24	1.98	2.07	.185	.141	.160	1.05	0.867	0.648	1.13	1.13	1.207	.236	.236	.221
Average ..	—	—	—	2.16	1.99	2.08	.189	.136	.159	1.07	0.841	0.725	0.776	1.08	1.12	.223	.237	.214

season (tables 1 and 2). For the purposes of this study a sampling period in July seemed to represent a time of minimum fluctuation in elemental composition of white oak leaves. Sampling at that one time enabled the writer to investigate a greater number of areas. The nitrogen concentration in leaves of trees from both immature Ava silt loam and Bluford silt loam decreased as the growing season advanced, but this tendency was not so pronounced as that observed by McHargue and Roy (6) and Alway *et al.* (1) in their studies of leaves of forest trees. Table 1 indicates clearly a plateau from early July until mid-September where the concentration of nitrogen in the leaves studied remained virtually con-

stant. A similar situation is revealed by the data of Samson and Samisch (9) Alway *et al.* (1), and Mitchell (7). The decreased concentration of nitrogen in the leaves as the growing season advances can largely be accounted for by postulating that most of the nitrogen accumulated in the leaves at an early stage of growth and that subsequent leaf growth resulted in the reduction in the nitrogen content per unit area of leaf. The data in table 2 indicate that another explanation must be sought for the sharp decline in nitrogen content of fallen and near-fallen leaves in contrast to that of growing leaves. Since the possibility of loss of nitrogen by leaching was excluded by the promptness of sampling, and because the percentage of nitrogen in growing leaves as contrasted to freshly

TABLE 2
Chemical composition of fallen and near-falling white oak leaves
Results in percentages, calculated on moisture-free basis

DATE OF SAMPLING	TREE DESIGNATION	SOIL TYPE	COUNTY	FIELD COMMENTS	N	K	P	Mg	Ca
Nov. 1, 1940	1	Clinton	Logan	Still fairly green	0.85		.100	.303	1.42
	1	Clinton	Logan	Freshly fallen	0.60	.58	.098	.310	1.35
	2	Clinton	Logan	Near-falling	0.62		.101	.332	1.72
	2	Clinton	Logan	Freshly fallen	0.57	.52	.085	.310	1.42
	3	Clinton	Logan	Near-falling	0.57		.097	.312	1.80
	3	Clinton	Logan	Freshly fallen	0.52	.52			1.41
Nov. 7, 1941	1	Clinton	Marshall	Some green color	0.61		.123	.209	2.07
	1	Clinton	Marshall	All chlorophyll gone	0.65		.165	.160	1.64
	1	Clinton	Marshall	Freshly fallen	0.64	.263	.114	.156	1.37
	2	Clinton	Marshall	Some green color	0.64		.139	.210	2.05
	2	Clinton	Marshall	All chlorophyll gone	0.61		.138	.191	1.64
	2	Clinton	Marshall	Freshly fallen	0.64	.543	.099	.177	1.33
	3	Clinton	Marshall	All chlorophyll gone	0.61	.334	.157	.191	1.63
	3	Clinton	Marshall	Some green color	0.59	.541	.135	.234	1.82
Nov. 8, 1941	2	Ava	Richland	Considerable green	0.78		.115	.245	1.20 ¹
	2	Ava	Richland	Considerable green	0.89	.248	.109	.215	1.43
	2	Ava	Richland	Freshly fallen	0.67	.340	.080	.273	1.14
	3	Bluford	Richland	Considerable green	1.39		.123	.201	1.10
	3	Bluford	Richland	Considerable green	1.43	.543	.126	.249	1.15
	3	Bluford	Richland	Freshly fallen	0.71		.070	.267	1.00

* All leaves except those indicated as freshly fallen were still attached to trees.

fallen leaves gave ratios greater than 3 to 1, it is suggested that there was resorption of the nitrogen from the leaves into the storage organs of the tree toward the close of the growing season.

Although Alway *et al.* (1) reported that the concentration of magnesia increased while the leaves were on the tree, a statistical analysis of their data shows no significant fluctuation in the percentage of Mg as the growing season advanced. Their data seem to agree with the findings of McHargue and Roy (6). The study reported in this paper showed that the percentage composition of Mg remained constant for leaves from both soil types from Wabash county during the growing season (table 1).

Investigators seem to be universally agreed that the concentration of Ca in oak leaves increases as the growing season advances. Tables 1 and 2 bear out

this reported increasing Ca content and indicate that the process continues to the near-falling stage. It would seem that Ca absorbed by the roots enters into the leaves in an organic form that is relatively insoluble and therefore is not subjected to backward translocation toward the end of the growing season.

McHargue and Roy (6) and Samson and Samisch (9) have reported a decreased concentration of P and K in oak leaves as the growing season advances. Mitchell (7), however, suggested that the absolute quantities of these elements in the leaves did not decrease appreciably from spring to fall. He observed that the N, P, and K concentrations of all leaf species studied by him decreased rapidly during early summer, but after midsummer these values tended to remain relatively constant. During periods of most rapid growth the increase in dry matter in the leaf exceeded the rate of flow of N, P, and K into the leaves, resulting in a dilution of the nutrient elements in the leaf and thus a decrease in percentage values. As the rate of leaf growth comes into equilibrium with the rate of movement of N, P, and K into the leaves, the dilution process became inoperative and the concentration values tended to remain constant during a large part of the growing season. Data for the white oak leaves from the Wabash County area (table 1) show a trend toward a decreased concentration of K as the growing season advanced. This trend was exhibited in leaves from trees growing on both soil types studied regardless of position on the tree. The data for fallen and near-falling leaves (table 2) indicate a tendency for the K concentration to drop decidedly at the end of the growing season. Some of the rather low values reported for K could have resulted from some leaching of the leaves while they were still attached to the tree, as it had rained a few days prior to sampling. When calculated on a dry weight basis, the difference between the total amount of K in growing leaves and in fallen leaves indicated that there had been movement of K from the leaves into the storage tissues of the trees before leaf fall. The data in table 1 do not indicate a definite trend toward decreased P concentration as the growing season advanced, but indicate a time of peak concentration during the early part of the growing season followed by a drop in the concentration of P in the leaves. After this drop, the percentage values for that element fluctuate very little throughout the remainder of the growing season, though the concentration of P seems to decrease sharply just before leaf fall (table 2).

Influence of soil types and composition on chemical composition of leaves

A statistical study of the data in table 3 (table 5) indicated for the elemental composition of white oak leaves the following pertinent facts: Leaves produced on Ava and Clinton silt loams contained significantly greater amounts of Ca than those grown on Bluford silt loam. The Ca content of leaves from immature Ava silt loam was significantly greater than that of leaves grown on Bluford silt loam. The Mg content of leaves grown on Clinton silt loam was significantly greater than that of leaves grown on Bluford silt loam, but there were no significant differences in the Mg content of leaves from Ava, immature Ava, and Bluford silt loams. The K contents of the leaves from the various soil types were

not significantly different, although statistical significance was approached in the greater K content of the leaves from Ava silt loam as contrasted to those from Bluford silt loam. There were significantly larger amounts of phosphorus in leaves from Clinton silt loam than in those from Bluford and Ava silt loams, and statistical significance was approached very closely when the P content of leaves from Clinton silt loam was compared with that of leaves from immature Ava silt loams. Differences were considered significant when the "*P* values" corresponding to the calculated "*t* values" were 0.05 or less according to tables by Fisher (5).

The studies made at the soil pits showed the major root concentration to be in the A horizons. It was therefore assumed that the white oak trees fed primarily from these horizons. The Ca and the K content of the leaves tends to increase slightly with the increasing pH value of the A horizon of the soil (tables 3 and 4). Table 6 shows, however, that there were no significant correlations, at the 0.05

TABLE 3

Composition of white oak leaves from trees growing on different soils during mid-July 1939, 1940, and 1941

Average values from three trees for 3 years, in percentages, calculated on moisture-free basis

SOIL	COUNTY	LEAF COMPOSITION				
		N	K	P	Mg	Ca
Bluford	Richland, Macoupin	2.05 ± .04	0.925 ± .061	.155 ± .008	.186 ± .032	1.00 ± .06
Immature Bluford	St. Clair	1.85 ± .005	0.93 ± .08	.138 ± .005	.216 ± .004	1.21 ± .08
Ava	Richland, Fayette	2.04 ± .06	1.108 ± .315	.152 ± .003	.212 ± .011	1.29 ± .08
Immature Ava	St. Clair, Wabash	1.88 ± .04	1.01 ± .06	.161 ± .006	.216 ± .013	1.19 ± .06
Clement	Wabash	1.94 ± .03	1.00 ± .03	.150 ± .004	.198 ± .018	1.13 ± .03
Immature Clement	Wabash	1.92 ± .06	0.96 ± .01	.153 ± .005	.231 ± .02	1.38 ± .15
Clinton	Ogle, Marshall, Logan	2.01 ± .04	1.02 ± .03	.192 ± .012	.226 ± .005	1.20 ± .04

level, between the P, K, Mg, Ca, or the Ca-Mg ratio of the white oak leaves and the corresponding values for the soils on which the trees were growing. On this basis the present study shows some evidence of the influence of soil type but little influence of soil composition on the chemical composition of white oak leaves. It would seem that the ability of the roots of the white oak tree to "forage" for the essential mineral constituents in the soil is such that even soils comparatively low in replaceable bases contain adequate amounts for leaf growth (figs. 1 and 2).

The number of soil analyses available are not sufficient, however, to establish whether there are significant differences in the chemical composition of the soil types. The data relating the percentage saturation with Ca and the Ca-Mg ratio in the A horizons to the percentage Ca in the leaves grown on these soils (table 6) show a direct correlation between the two pairs of variables. The chances are greater than 8 out of 10 that this correlation is not due to chance. Probably, in certain areas both the chemical composition of the soil type and its other properties influence the composition of plants growing on the soil. Possibly environmental factors not expressed by soil type also influence leaf composition.

TABLE 4

Chemical properties of soil profiles on which chemical composition of white oak leaves was studied

SAMPLE NO.	TREE	SOIL NUMBER AND COUNTY	HORIZONS (COMPOSITED)	THICKNESS	WEIGHT OF SAMPLE	pH	AVAILABLE* P	EXCHANGEABLE K	EXCHANGEABLE Mg	EXCHANGEABLE Ca	TOTAL BASES	BASE-EXCHANGE CAPACITY
				inches	gm.		lb./A.	me.	me.	me.	me.	me.
S 16 772	3	Bluford, 13, Richland	A	17	1553	5.4	18	.237	1.83	2.8	4.1	10.1
S 16 773	3		B	17	2203	4.7	17	.213	3.03	1.82	5.42	14.3
S 16 780	3	Immature Bluford, 164, St. Clair	A	20	1902	4.4	36	.228	0.92	1.7	2.80	11.0
S 16 781	3		B	20	2202	4.1	54	.297	6.99	4.77	11.5	27.9
S 16 774	1	Immature Clement, 215, Wabash	A	8.4	658	4.9	156	.374	1.63	6.17	8.05	14.1
S 16 775	1		B	20.2	1747	4.8	120	.36	4.26	2.6	7.12	19.45
S 16 667	3	Immature Ava, 214, Wabash	A	17	1540	4.9	24	.22	1.50	1.97	3.57	11.7
S 16 777	3		B	19	2170	4.5	24	.277	5.10	3.87	9.12	14.85
S 16 778	1	Immature Ava, 214, St. Clair	A	20	1933	4.4	30	.246	1.50	1.66	3.30	14.6
S 16 779	1		B	20	2430	4.2	77	.287	6.47	3.9	10.65	24.61
S 16 782	2	Immature Ava, 214, St. Clair	A	15.6	1370	4.6	96	.333	1.21	3.27	4.7	10.2
S 16 783	2		B	24.4	2895	4.7	212	.385	4.75	8.65	13.4	20.1
S 16 784	3	Immature Ava, 214, St. Clair	A	15.1	1327	4.6	96	.309	1.33	2.27	4.0	8.5
S 16 785	3		B	24.9	3039	4.7	187	.374	5.41	7.6	12.9	18.55
S 16 786	2	Clinton, 18, Logan	A	15.2	1015	5.2	30	.318	3.21	5.72	9.15	15.2
S 16 787	2		B	24.8	2080	5.1	55	.309	7.39	10.8	18.3	21.75
S 16 788	3	Clinton, 18, Logan	A	15	848	5.8	37	.309	2.29	3.57	5.7	14.25
S 16 789	3		B	25	2080	5.8	64	.318	7.06	9.45	16.7	22.1
S 16 790	3	Clinton, 18, Ogle	A	13.7	955	5.8	30	.318	2.48	4.05	6.5	14.42
S 16 791	3		B	26.3	2118	4.8	102	.297	5.43	9.57	15.2	24.35
S 16 792	1	Clinton, 18, Ogle	A	15.6	1098	4.8	70	.331	1.87	4.95	7.05	15.37
S 16 793	1		B	24.4	2140	4.9	116	.297	5.56	9.87	15.85	20.72
S 16 794	2	Clinton, 18, Ogle	A	15	1055	5.0	55	.343	2.32	5.65	8.3	19.82
S 16 795	2		B	25	2010	4.8	120	.277	5.01	10.2	15.85	21.47
S 16 796	1	Clinton, 18, Marshall	A	15.5	1010	5.0	42	.287	1.54	4.45	6.0	12.67
S 16 797	1		B	24.5	2020	4.7	72	.356	5.40	9.1	14.95	22.42
S 16 798	2	Clinton, 18, Marshall	A	13.7	915	4.9	42	.309	1.40	3.0	4.7	9.97
S 16 799	2		B	26.3	2063	4.7	89	.331	4.02	8.9	12.92	21.87
S 16 800	3	Clinton, 18, Marshall	A	14.5	1037	4.8	40	.343	1.68	3.85	5.62	12.4
S 16 801	3		B	25.5	2045	4.7	68	.356	5.49	9.82	15.6	22.6
S 16 802	1	Ava, 14, Fayette	A	16.2	1217	5.0	38	.331	1.58	3.9	5.7	11.35
S 16 803	1		B	23.8	2185	4.6	84	.314	3.86	5.57	10.0	19.2
S 16 804	2	Ava, 14, Fayette	A	16.5	1305	5.4	44	.277	1.49	5.05	6.2	11.37
S 16 805	2		B	23.5	2005	4.9	43	.309	4.36	8.75	13.2	19.4
S 16 806	3	Ava, 14, Fayette	A	15.15	1119	5.4	45	.309	1.74	6.5	8.0	13.35
S 16 807	3		B	24.85	2198	5.8	70	.256	3.53	9.9	13.3	21.45
S 16 770	2	Ava, 14, Richland	A	18	1830	5.0	17	.228	1.64	1.5	3.33	10.72
S 16 771	2		B	18	1769	4.5	16	.246	3.9	1.55	6.10	18.7

* Illinois P₁ soil test.

TABLE 5
Statistical study of leaf composition by soil types
 Based on table 3

	DE- GREES OF FREE- DOM	STANDARD ERROR OF DIFFERENCE	D/ED	P* VALUES	
	n	E_D	t		
I Calcium content of leaves					
Blufords compared to Clintons.....	23	.0674	3.26	< .01	
Blufords compared to Avas.....	14	.095	3.05	< .01	
Blufords compared to immature Avas.....	17	.0887	2.14	< .05	> .02
Avas compared to immature Avas. .	15	.102	0.98	< .4	> .3
Clinton compared to Avas.....	15	.080	0.875	< .4	> .3
Clintons compared to immature Avas.	24	.077	0.390	< .7	
II Magnesium content of leaves					
Blufords compared to Clintons.....	23	.0115	3.39	< .01	
Blufords compared to immature Avas.	16	.016	1.94	< .2	> .1
Blufords compared to Avas.	14	.014	1.8	< .1	> .05
III Potassium content of leaves					
Avas compared to immature Avas .	15	.109	1.1	< .3	> .2
Avas compared to Blufords	14	.115	2.09	< .1	> .05
Avas compared to Clintons.....	21	.0994	0.91	< .4	> .3
IV Phosphorus content of leaves					
Clintons compared to immature Avas.	23	.0125	1.76	< .1	> .05
Clintons compared to Avas.	19	.0112	2.23	< .05	> .02
Clintons compared to Blufords..	21	.0127	2.12	< .05	> .02

* According to table of "t" values by R. A. Fisher (5), where P value of 0.05 or less is considered as test of significance.

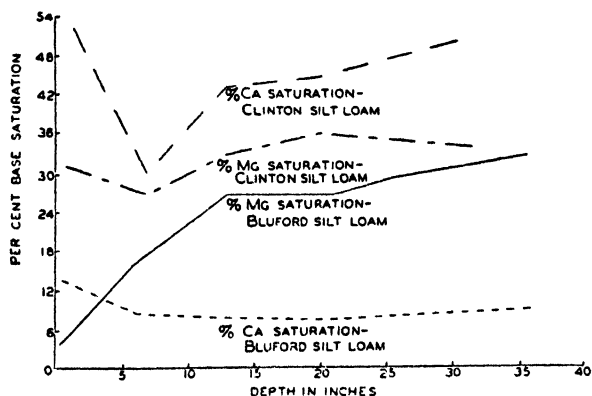


FIG. 1. DISTRIBUTION OF EXCHANGE COMPLEX SATURATION WITH CA AND MG IN CLINTON AND BLUFORD SILT LOAM PROFILES

Serex (10), one of the earliest workers on this problem, reported the lowest percentages of N and P for leaves from Suffield clay which was considered more fertile than the Holyoke stony loam and Wethersfield loam studied. Mitchell (7) reported that the intake of nutrients depended upon the external supply and the absorbing power of the roots; thus, the foliage of a tree growing on a given

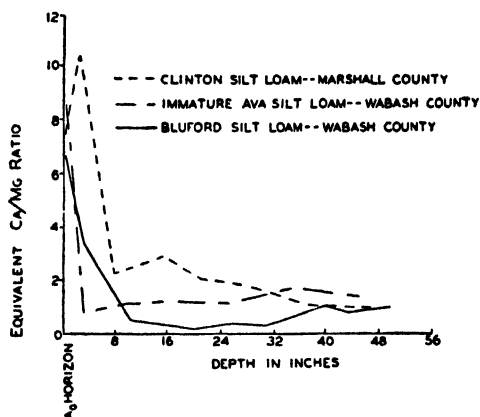


FIG. 2. DISTRIBUTION OF EXCHANGEABLE CA/MG IN SOIL PROFILES

TABLE 6

Correlation coefficients for leaf composition with composition of soil A horizon as the independent variable

Based on tables 3 and 4

	INDEPENDENT VARIABLE (MEAN VALUE)	DEPENDENT VARIABLE (MEAN VALUE)	CORRELA- TION COEFFICIENT (<i>r</i>)	<i>t</i> VALUE (CALCU- LATED)	<i>P</i> VALUE
		<i>per cent</i>			
Phosphorus	50 lb./A.	0.167	.276	.119	> .9
Potassium	2.43 per cent saturation (of total bases)	0.995	.103	.426	.7 < > .6
Magnesium	15 per cent saturation (of total bases)	0.219	.071	.293	.8 < > .7
Calcium	30.1 per cent saturation (of total bases)	1.25	.371	.164	.1 < > .2
Ca/Mg ratio	2.25	3.45	.37	.164	.1 < > .2

soil complex should be a good index of the mineral supplying power of the soil. Burger (3) and Plice (8) observed a correlation between the principal bases and nitrogen found in tree leaves and the presence or absence of carbonates in the soil. The data of both investigators seem to show a tendency toward constancy of chemical composition for the leaves of a given tree species, within limits, regardless of soil type, for any given location. Chandler (4), in his study of the leaf litter of the hardwood forests of central New York, reported that the N and

Ca contents of the leaves expressed on a percentage basis were not significantly different on the more productive and less productive soil types. He found that the Mg content of leaves was higher and the P and K contents were slightly lower on the productive soils, and attributed differences in the average mineral nutrient content of leaf litter mainly to inherent differences among the various individual species rather than to the influence of soil type.

SUMMARY AND CONCLUSIONS

White oak leaves from various soil types in Illinois were collected and analyzed chemically. A study was made of physical and chemical properties of the soils on which the trees grew. Leaf compositions were correlated statistically with the soil type characteristics investigated.

It was observed that the percentage of Ca in the leaf increased as the season advanced, whereas the Mg content remained fairly constant throughout the growing season. The concentrations of K, P, and N in white oak leaves decreased as the season advanced.

This investigation shows some evidence of the influence of soil type on the chemical composition of white oak leaves. Only when the poorest soils (Bluford) were compared to the best soils (Clinton), however, was a significant influence of soil type on leaf composition observed.

Statistical study of the leaf composition data indicated that the Ca content of leaves from the Bluford soils was significantly lower than that of leaves from the Clinton, Ava, and immature Ava soils. The Mg contents of leaves grown on Clinton silt loam were significantly greater than those of leaves grown on Bluford silt loam. The K contents of leaves did not differ significantly among soil types. The phosphorus contents of leaves from Clinton silt loam were significantly greater than those from Ava and Bluford silt loams.

No significant correlations could be observed between the K, P, Mg, and Ca contents or Ca-Mg ratio of the white oak leaves and the corresponding values for the A horizons of the soils on which the trees were growing. It seems that the ability of the roots of white oak trees to forage for the essential mineral nutrients in the soil is such that even soils comparatively low in replaceable bases contain nutrients in amounts adequate for leaf growth. Other environmental factors expressed by the soil type and possibly environmental factors not expressed by the soil type apparently influence leaf composition.

REFERENCES

- (1) ALWAY, F. J., MAKI, T. B., AND METHLEY, W. J. 1934 Composition of the leaves of some forest trees. *Amer. Soil Survey Assoc. Bul.* 15: 81-84.
- (2) BRAY, R. H. Rapid tests for measuring and differentiating between the adsorbed and acid-soluble forms of phosphate in soils. Dept. Agron., Univ. of Ill., Urbana.
- (3) BURGER, H. 1931 Holzarten auf verschiedenen Bodenarten Schweiz. *Centralanst. Forstl. Versuchsw. Mitt.* 16: 49-128 1931.
- (4) CHANDLER, R. F. 1941 The amount and mineral nutrient content of freshly fallen leaf litter in the hardwood forests of central New York. *Jour. Amer. Soc. Agron.* 33: 859-871.

- (5) FISHER, R. A. 1938 *Statistical Methods for Research Workers*, ed. 10. Oliver & Boyd, Edinburgh.
- (6) MCHARGUE, J. S., AND ROY, W. R. 1932 Mineral and nitrogen content of the leaves of some forest trees at different times in the growing season. *Bot. Gaz.* 94: 381-393.
- (7) MITCHELL, H. L. 1936 Trends in the nitrogen, phosphorus, potassium and calcium content of the leaves of some forest trees during the growing season. *Black Rock Forest Paper*: 1 (6).
- (8) PLICE, M. J. 1934 Acidity, antacid buffering and nutrient content of forest litter in relation to humus and soil. N. Y. (Cornell) *Agr. Exp. Sta. Mem.* 166.
- (9) SAMPSON, A. W., AND SAMISCH, R. 1935 Growth and seasonal changes in the composition of oak leaves. *Plant Physiol.* 10: 739-751.
- (10) SEREX, P. 1917 Plant food materials in the leaves of forest trees. *Amer. Chem. Soc. Jour.* 39: 1286-1296.

SOME PHASE-MICROSCOPE OBSERVATIONS OF *AZOTOBACTER AGILE*¹

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The nature of the bacterial nucleus, life cycles of bacteria, and general cytological properties of microorganisms need to be reinvestigated in the light of newer techniques and methods. The mode of reproduction of *Azotobacter*, for example, has always been a matter of controversy among bacteriologists (1, 2). The peculiar morphological variations which occur have led to many interpretations. Actual "proof" to support hypotheses has been difficult to establish because of the limitations of microscopic techniques. Further evidence may now be possible through newer devices. One of these is the phase microscope (3), which gives added contrast to structures within biological preparations, especially where these structures have only slight variation of refractive index.

The purpose of this study was to develop a suitable technique for producing maximum visibility of cytological structures of *Azotobacter agile* with the use of phase-contrast accessories. Since phase microscopy alone failed to reveal all cell structures, combinations of techniques were tried. Use of a background stain along with osmium tetroxide fixation and phase microscopy gave best results. Bausch and Lomb phase accessories were used in this study.

MATERIALS AND METHODS

The following procedure was used to produce distinct visibility of structures of *Azotobacter* cells:

Step 1. Suspension of *Azotobacter agile* cells (24-hour slant) in 0.85 per cent saline and placing a drop of this suspension on a microscope slide.

Step 2. Allowing the suspension to come in contact with osmium tetroxide vapors for 30 minutes to fix cells.

Step 3. Mixing suspension with a very small drop of nigrosin, spreading into a thin film, and allowing to air-dry.

Step 4. Observation under oil immersion, using phase microscopy.

In addition to slides prepared in this manner, other slides were made in which the third step of mixing with nigrosin was omitted. This brought out the importance of using a background stain, as may be seen from the photographed results. Other comparisons were made with *Azotobacter*, using standard procedures of gram staining, capsule staining, and simple methylene blue staining.

RESULTS

Internal structures of *Azotobacter agile* are evident in figures 1, 2, 3, and 4, which are photographs of negative stains taken under the phase microscope.

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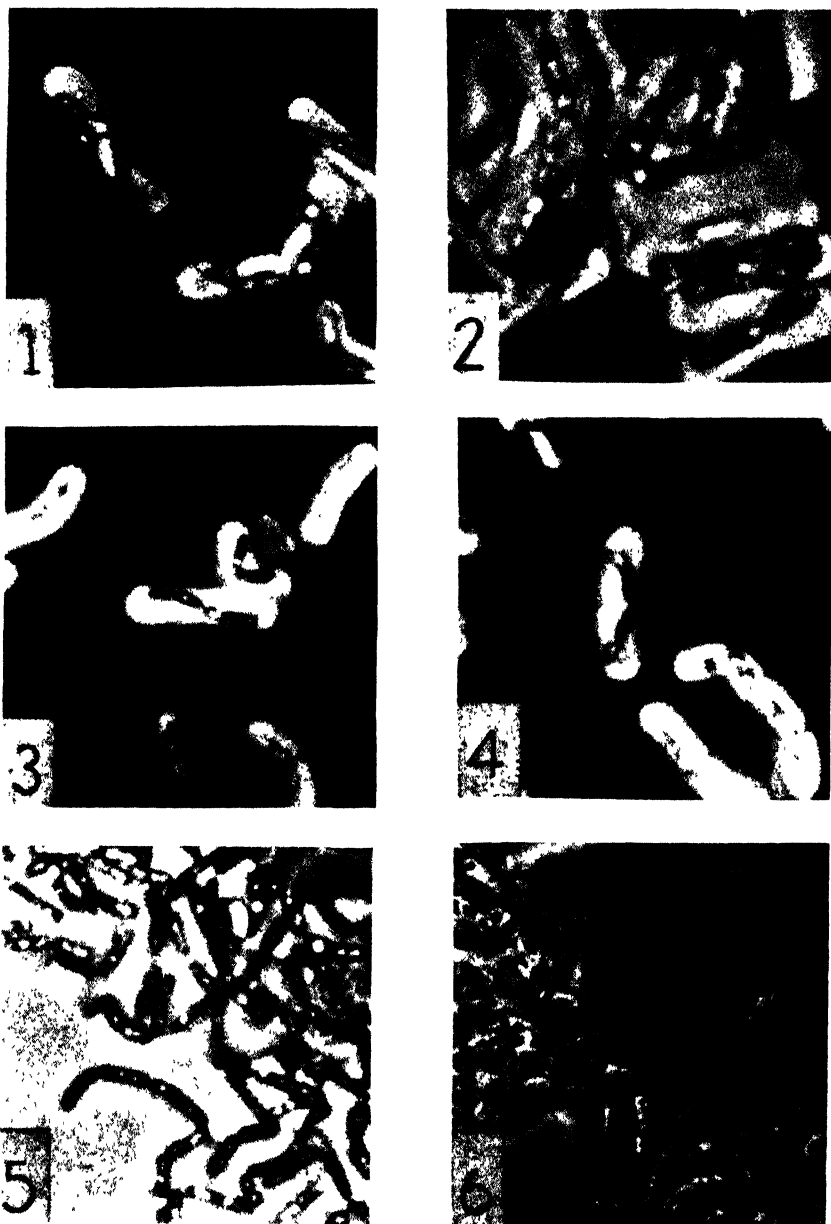


PLATE 1

Figs. 1, 2, 3, and 4 Nigrosin background smears of *Azotobacter agile*, showing distinct central structures (nuclei?) and external clear area (cytoplasm?). Figs. 5 and 6. Unstained preparations of *Azotobacter agile*, with only the central bodies showing up distinctly. All photographs were taken under a phase-contrast microscope with a Bausch and Lomb photomicrographic camera (type J) on 5- by 7-inch film. The original photographs were made at 2,000 magnification and enlarged to the scale indicated on figure 3.

Immediate observation might lead one to the conclusion that the clear zone surrounding the internal dark areas represents the capsule or slime layer. This area, however, failed to take capsule stains, failed to wash away even after many hours of shaking in distilled water, and was readily stained by the gram method and other stains normally used in bacteriology. This leads to the opinion that the clear area surrounding the internal structure does not represent the usual polysaccharide capsule or slime layer of other bacteria. Perhaps these *Azotobacter* cells are differentiated into true cytoplasmic areas and true nuclear areas, as are the cells of higher organisms.

All attempts to make the same observations without phase microscopy failed to produce sharp differentiations. As may be seen in figures 5 and 6, omission of the nigrosin results in loss of vision of the external area. Figures 5 and 6 are pictures of the same field, except that one represents a different focus level of the other.

The arrangement of the internal bodies in all preparations resembles somewhat the arrangement of the "chromosomes" in various bacteria described by Robinow (4). This would indicate that they possibly are desoxyribonucleo protein and may represent the chromatin material of the *Azotobacter* cells studied.

SUMMARY

Improved visibility of structures in *Azotobacter agile* cells was obtained by use of phase microscopy. Bacteria were first fixed in osmium tetroxide fumes and stained with nigrosin, a negative background stain. This resulted in sharp differentiation into central bodies and an external area (cytoplasm?). Attempts to determine the chemical nature of the external area suggested that it did not contain the polysaccharide material common to the capsules or slime layers of other bacteria.

REFERENCES

- (1) LEWIS, I. M. 1937 Cell inclusions and the life cycle of *Azotobacter*. *Jour. Bact.* 34: 191-203.
- (2) LOHNIS, F., AND SMITH, N. R. 1923 Studies upon the life cycles of the bacteria: II. Life history of *Azotobacter*. *Jour. Agr. Res.* 23: 401-432.
- (3) RICHARDS, O. W. 1948 Phase microscopy in bacteriology. *Stain Technol.* 23: 55-64.
- (4) ROBINOW, C. F. 1944 Cytological observations on *Bact. coli*, *Proteus vulgaris*, and various aerobic spore-forming bacteria with special reference to the nuclear structures. *Jour. Hvg.* 43: 413-423.

PROFILE STUDIES OF NORMAL SOILS OF NEW YORK:

II. MICROMORPHOLOGICAL STUDIES OF THE GRAY-BROWN PODZOLIC—BROWN PODZOLIC SOIL SEQUENCE

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Although gray-brown podzolic and brown podzolic soils are generally considered zonal soils of different climatic regions, both kinds of profiles occur in the same area in central and western New York. The gray-brown podzolic soils in this area are confined to calcareous parent materials; brown podzolic soils occur wherever parent materials are acid and appear to be developing within the solums of gray-brown podzolic soils wherever bases have been depleted. These observations have led to the hypothesis that brown podzolic soils are normal for the region and will replace gray-brown podzolic profiles on calcareous materials if bases are depleted (4).

In many places in New York, lime in glacial deposits decreases with distance from the outcrop of lime-bearing rocks. In these places, the soils near the lime-bearing outcrops have typical gray-brown podzolic profiles, but as lime in the parent material decreases, the upper part of the solum increases in acidity and acquires horizons characteristic of brown podzolic soils (4). These geographic sequences provide a continuous series of profiles the base status of which may be assumed to be comparable to progressive stages in the depletion of bases with time on an originally calcareous material. In the work reported here, the major horizons of six profiles in such a sequence were studied in thin section by means of the petrographic microscope.

PROCEDURE

Sampling sites were chosen to provide three profiles of the gray-brown podzolic Ontario series and three profiles of the brown podzolic Sodus series. In the area selected, properties of the Ontario soils become less distinctive and those of the Sodus soils become more distinctive as lime in the parent material decreases. The profiles were selected to provide a modal profile and intergrades representing the high- and low-lime extremes of each series. The array of six profiles provided six levels of base status comparable to six stages of base-depletion on calcareous materials. The profiles ranged from a strongly expressed gray-brown podzolic soil, which was nearly neutral throughout the solum, to a very strongly acid brown podzolic soil with neutral or weakly calcareous material deep in the substratum. The profiles are described in the first paper of this series (4), and the

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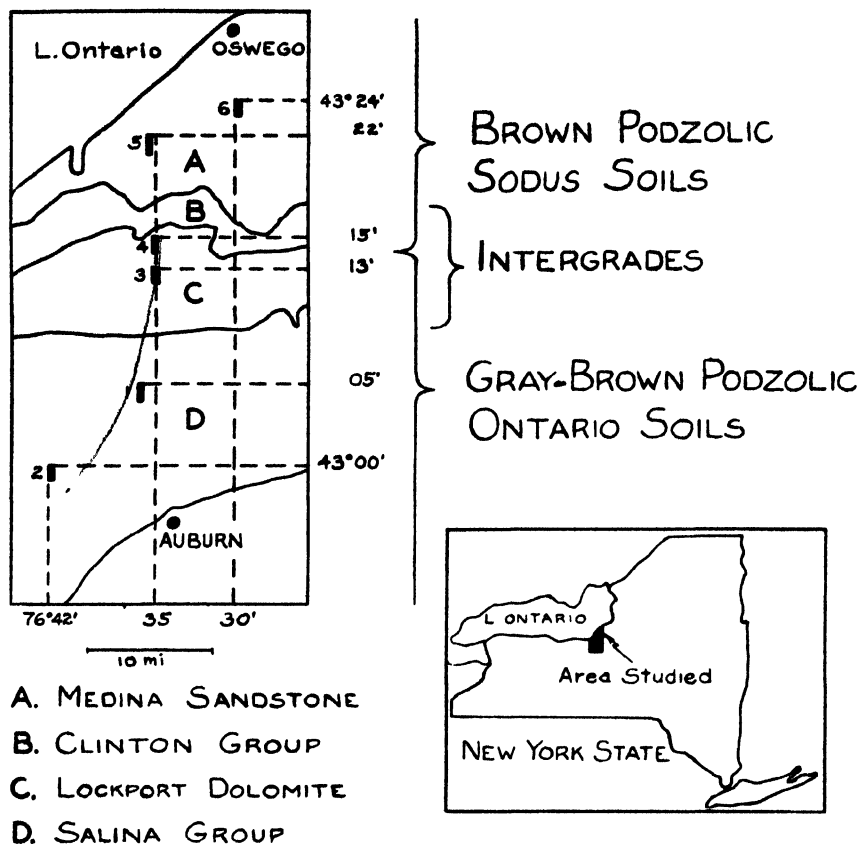


FIG. 1. SAMPLING SITES AND RELATIONSHIPS TO BEDROCK GEOLOGY OF THE SIX PROFILES STUDIED

TABLE 1

Climatic factors in the area studied and in regions of gray-brown podzolic soils and podzols (10, 18)

STATION	ELEVATION ABOVE SEA LEVEL	LENGTH OF GROW- ING SEASON	MEAN ANNUAL TEMPERATURE		MEAN ANNUAL PRECIPITATION		P/T RATIO
			°F.	°C.	in.	cm.	
<i>Area studied</i>							
Auburn, N. Y.	715	168	47	8.3	37	92	11
Oswego, N. Y.	335	183	46	7.8	36	90	12
<i>Gray-brown podzolic soil region</i>							
Columbus, Ohio.	725	187	54	12.2	34	86	7
<i>Podzol region</i>							
Gabriels, N. Y.	1750	97	40	4.4	37	92	21

sampling sites and their relationships to bedrock geology (8, 9) are shown in figure 1.

TABLE 2

Relative numbers* of the more prominent forest plants on the sites sampled

	GRAY-BROWN PODZOLIC ONTARIO SOIL		INTERGRADES		BROWN PODZOLIC SODUS SOIL
	Site 1	Site 2	Site 3	Site 4	Site 6
Approximate age of the oldest trees					
years	60	20-30	60-80	80-100	40-60
Covering of soil surface by ground vegetation	1/10	1/4	1/3	1/3	1/10
<i>Trees</i>					
<i>Acer saccharum</i>	5	—	2	5	4
<i>Fagus grandifolia</i>	1	—	2	2	3
<i>Betula lutea</i>	—	—	—	—	1
<i>Tsuga canadensis</i>	—	—	(+)	—	1
<i>Tilia americana</i>	2	—	3	1	+
<i>Frazinus americana</i>	1	2	1	—	+
<i>Ulmus americana</i>	1	—	—	—	—
<i>Quercus borealis</i>	—	2	—	—	—
<i>Prunus serotina</i>	—	5	—	—	(+)
<i>Ground vegetation</i>					
<i>Polygonatum biflora</i>	1	—	+	2	1
<i>Aspidium simulatum</i>	—	—	+	+	1
<i>Vitis vulpina</i>	—	+	+	+	1
<i>Psedera quinquefolia</i>	—	—	—	+	1
<i>Maianthemum canadense</i>	—	—	—	—	1
<i>Impatiens pallida</i>	—	—	+	1	—
<i>Adiantum pedatum</i>	—	—	+	—	—
<i>Polystichum acrostichoides</i>	1	+	+	—	+
<i>Trillium erectum</i>	+	1	2	+	1
<i>Actea rubra</i>	—	1	—	—	+
<i>Viola</i> sp.	+	—	—	—	+
<i>Carex</i> sp.	—	—	+	—	+
<i>Allium tricoccum</i>	1	—	—	—	—
<i>Actea alba</i>	1	—	+	—	—
<i>Geranium maculatum</i>	2	—	—	1	—
<i>Geranium robertianum</i>	—	+	—	—	—
<i>Smilacina racemosa</i>	+	+	2	+	—
<i>Caulophyllum thalictroides</i>	1	1	+	—	—
<i>Podophyllum peltatum</i>	1	1	—	—	—

* 5 = very many; 4 - 2 = many - few; 1 = very few; + = single plants; (+) = very poor plants only; — = none.

Variations of climate, relief, and time were held to a minimum, but parent material and co-varying vegetation were allowed to range widely among sampling sites. The range of climatic factors is shown in table 1. All of the sampling sites

were on slopes between 1 and 5 per cent in gradient near the crests of drumlins. Differences in time since the till was exposed would be minor in relation to the length of time since glaciation (6). Lime in the parent material, however, decreased generally from south to north in the area as a result of dilution of the predominantly acid Medina sandstone material with calcareous material from the Clinton, Lockport, and Salina formations as the ice moved southward (fig. 1). This variation of parent material was probably associated with systematic variation of native vegetation from north to south, although a positive statement cannot be made on the basis of the present vegetative cover. An incomplete list of the forest plants present at the time of sampling (table 2) indicates a general increase of high-calcium species from north to south in the area. The vegetation had been disturbed on all sites, however; site 2 had apparently been almost clear-cut, and site 5 was under cultivation. The effects on the soil, however, had apparently been confined to the topmost horizon on all sites.

A pit deep enough to permit sampling of the parent material was dug at each site, and genetic horizons were delineated on the face of each pit. Each horizon was sampled after the overlying soil was cut away and a horizontal surface was brushed free of all debris near the middle of the horizon. Samples were taken by forcing a Coile sampler (5) vertically into the soil. If soil structure was appreciably disturbed in the process, the sample was discarded and another sample of the same horizon was taken. Excess soil was trimmed from each end of the cylinder with a sharp knife, and the sample, still in the cylinder, was placed in a metal container for transportation to the laboratory.

The samples were air-dried and saturated with resin.² After the resin had hardened, a section of the sample was ground to a plane surface on one side, fixed on a glass slide with the resin, and ground to a thickness of about 50 to 80 μ with carborundum as described by Frei (7). The slides were studied under the petrographic microscope, and 2 by 2 kodachrome photomicrographs at various magnifications were prepared as a permanent record of the micromorphological properties of each horizon.

INTERPRETATION OF PHOTOMICROGRAPHS

Horizons of organic-matter accumulation

The condition of the surface horizon is closely related to the vegetation and the biological activity in the soil. There is every evidence of high biological activity in the A horizon of the Ontario soil (fig. 2). The organic matter is thoroughly mixed with the inorganic fraction, and practically none of the original vegetative forms can be identified. Soil aggregation is highly developed, and organic matter appears to be a principal cementing agent. Pore spaces among the aggregates are large; physical properties of the horizon are excellent.

The humus layer of the Sodus soil is quite different, as indicated in figure 3. Biological activity is much lower, and organic matter is much less well decomposed. The original cell structure of the plant residues can be seen near the top

² Sold as "natural resin for thin sections" by Firma Vernicolor in Meilen, Switzerland.

of the figure, and aggregates of humified materials are apparent near the bottom. The organic material is almost entirely unmixed with mineral soil. The animal population in the soil appears to have been limited mainly to small species that

FIG. 2

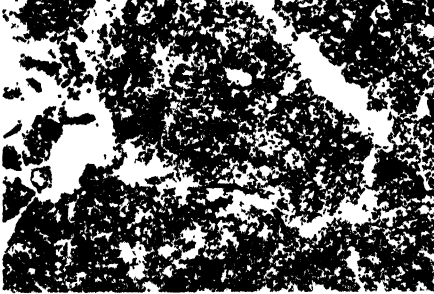


FIG. 3

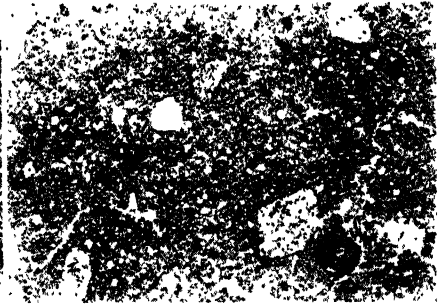
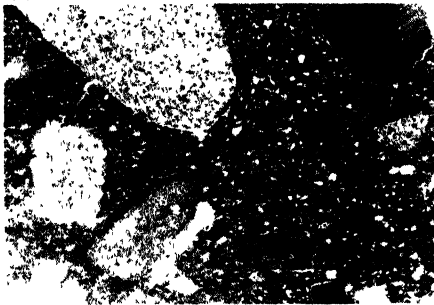


FIG. 4

FIG. 5

FIG. 2. VERTICAL THIN SECTION OF A_1 HORIZON AT A DEPTH OF 2 INCHES IN ONTARIO LOAM, PROFILE 2, AT $4.5 \times$ MAGNIFICATION

Biological activity is high, organic matter and mineral material are thoroughly mixed; stable aggregates bound by organic matter make a good spongelike fabric

FIG. 3. VERTICAL THIN SECTION OF A_0 HORIZON AT ITS CONTACT WITH THIN A_1 IN SODIC LOAM, PROFILE 6, AT $3.3 \times$ MAGNIFICATION

Biological activity is low, organic material is poorly decomposed and almost unmixed with mineral soil

FIG. 4. VERTICAL THIN SECTION OF C HORIZON AT A DEPTH OF 45 INCHES IN ONTARIO LOAM, PROFILE 1, AT $4.5 \times$ MAGNIFICATION

Aggregation is poor; pores are fine, clay concentrations are absent, limestone fragments are numerous

FIG. 5. HORIZONTAL THIN SECTION OF C HORIZON AT A DEPTH OF 64 INCHES IN SODIC LOAM, PROFILE 5, AT $4.5 \times$ MAGNIFICATION

Aggregation is poor; pores are fine; clay concentration, are absent; limestone fragments are absent.

were not able to bring about much soil mixing. This horizon is very similar to the corresponding layer in Podzol profiles.

The humus layers in profiles 1, 2, and 3 were essentially similar to that shown in figure 2. Profiles 4 and 6 had more humus layers with morphology like that of figure 3; profile 5 had been disturbed by cultivation, but fragments of plant tissue comparable to those of figure 3 were present in the plowed layer.

Inorganic leached horizons

Figure 6 is an enlargement of a section from the A_2 horizon of the Ontario soil. Figure 8 is an enlargement of a section from the lower part of the A_2 horizon

FIG 7

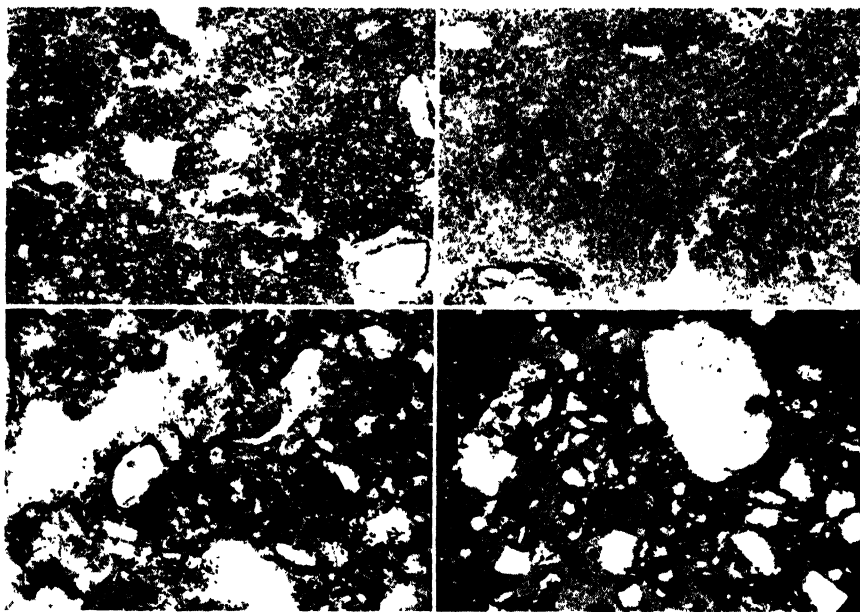


FIG 8

FIG 9

FIG. 6. VERTICAL THIN SECTION OF A_2 HORIZON AT A DEPTH OF 9 INCHES IN ONTARIO LOAM, PROFILE 2, AT $15 \times$ MAGNIFICATION

Numerous large pores occur, but the structure is not stable; small concretions and thin coatings of sesquioxides appear as dark areas

FIG. 7. VERTICAL THIN SECTION OF B_{21} HORIZON AT A DEPTH OF 11 INCHES IN SODUS LOAM, PROFILE 6, AT $4.5 \times$ MAGNIFICATION

The soil fabric is distinctly poorer than in the corresponding horizon of Ontario loam (fig. 6), pore spaces are small, structure is fine and unstable, the numerous dark spots are sesquioxide coatings and concretions.

FIG. 8. VERTICAL THIN SECTION OF A_{22} HORIZON AT A DEPTH OF 12 INCHES IN ONTARIO LOAM, PROFILE 1, AT $75 \times$ MAGNIFICATION

This high magnification of the lower part of A_2 horizon shows thin clay concentrations on the walls of some of the larger pore spaces.

FIG. 9. PART OF THE VERTICAL THIN SECTION OF B_{21} HORIZON OF SODUS LOAM OF FIGURE 7 AT $75 \times$ MAGNIFICATION UNDER POLARIZED LIGHT

Note the lack of double refraction in the sesquioxide films around the sand particles in the very loose weakly coherent fabric

of the same soil type. It will be noted in figure 6 that the soil fabric is less well developed than in the A_1 horizon shown in figure 2; the pore spaces are more uniform in size, and the edges of the aggregates are diffuse and irregular. Structure with these characteristics is generally unstable. In figure 8, which is from

the lower and grayest part of the A₂ horizon, very small dark-colored areas of clay concentration can be seen around the margins of some of the pore spaces. Close inspection discloses that these clays are arranged in distinct layers, a condition strongly developed in the principal horizon of clay concentration below. In the leached layer these small clayey bodies are confined to the lowest part of the A₂ horizon adjacent to the well-defined zone of clay accumulation, and, as a whole, the layer is light colored and mainly lacking in definitely clayey structures.

The corresponding horizon of the Sodus soil is the B₂₁ shown in figure 7. The architecture of the soil is weakly expressed; large soil aggregates are mainly lacking, and pore spaces are generally small. This slide was light yellowish red in contrast to the grayish color of the comparable horizon of the Ontario profile, and figure 9 shows the source of the color. Most of the sand particles in figure 9 are coated with thin dark films, which were yellowish red in the colored reproductions. These thin coatings show no double refraction under the petrographic microscope and are judged to be sesquioxides. They appear to have just enough adhesive properties to hold a few silt and sand particles together and form very small weak aggregates. These structures are pronounced only in profiles 4, 5, and 6 and are almost absent in the modal Ontario soil.

Brown clayey horizons with well-developed structure

Figure 10 is an enlargement of a section from the B₂₂ horizon of the Ontario soil. The well-developed nuciform structure is very characteristic; the aggregates are large and somewhat angular but have slightly rounded edges. The clear-cut definition of the aggregate surfaces suggests a high degree of stability. The dark parts are presumed to be accumulations of silicate clays which appear to have impregnated the outer parts of the aggregates.

Figure 12 is a part of the same section from which figure 10 was taken but shown at a greater magnification. Figure 13 is a photograph of the same area under polarized light through crossed nicols. Distinct banding of the clays along the light-colored pore space is evident in figure 12, and strong double refraction of these clayey layers is apparent from the light color of the band along the same pore space in figure 13. Extinction occurs simultaneously throughout long sections of this band when the microscope stage is rotated, which indicates a high degree of optical uniformity and suggests that the band may be composed of silicate clays that are highly oriented. The layering of clays is even more striking in figure 16, which is an enlargement of a slide taken from a depth of 50 inches in profile 4.

Figure 11 is a section from the comparable horizon deep in the Sodus soil. The characteristic well-developed platy structure and absence of large clay concentrations like those of figure 10 are apparent. Figure 14 at a greater magnification, however, shows a small area in the lower part that is occupied by layered clays, and figure 15, under polarized light and through crossed nicols, shows that these clays have optical properties like those observed in the Ontario soils. These small clay bodies are well inside the aggregates and are surrounded by materials

Fig. 10

Fig. 11

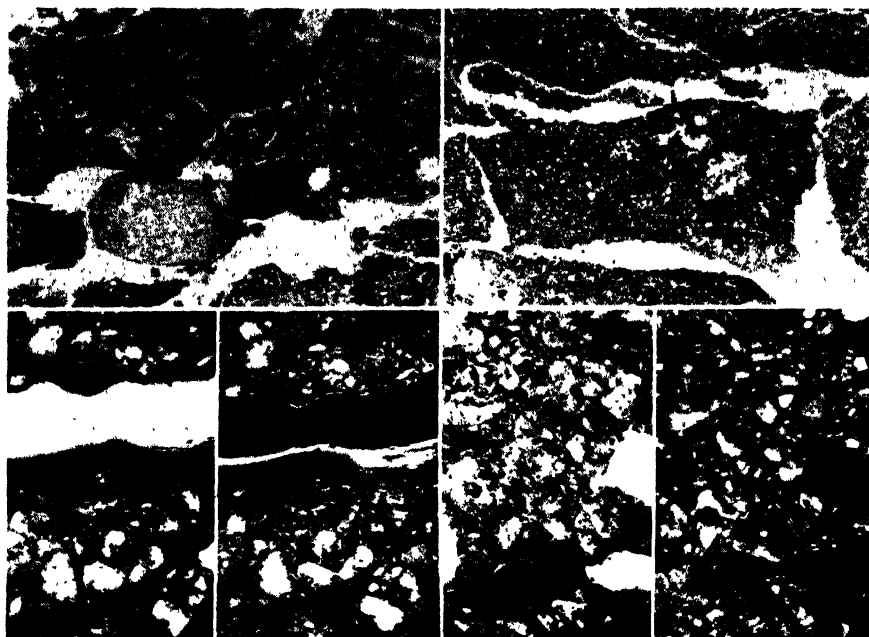


FIG 12

FIG 13

FIG 14

FIG 15

FIG. 10. VERTICAL THIN SECTION OF B₂ HORIZON AT A DEPTH OF 35 INCHES IN ONTARIO LOAM, PROFILE 1, AT 4.5 × MAGNIFICATION

Note the excellent nuciform structure and the dark accumulations of clay as crusts on the aggregates. Many large and small pore spaces form a very well developed soil fabric with the appearance of stability.

FIG. 11. VERTICAL THIN SECTION OF THE "FOSSIL" CLAYEY B HORIZON OF SODUS LOAM, PROFILE 6, AT A DEPTH OF 36 INCHES AT 4.5 × MAGNIFICATION

The well-developed platy structure is characteristic of this horizon. Note the lack of dark clay coatings on the aggregates such as are shown in figure 10.

FIG. 12. VERTICAL THIN SECTION OF B₂₂ HORIZON OF ONTARIO LOAM AT A DEPTH OF 32 INCHES, SAME HORIZON AS FIGURE 10 BUT AT 75 × MAGNIFICATION

This shows the surface of the soil aggregate highly impregnated with clays. Note the distinct layering of those clays at the outside of the aggregate.

FIG. 13. SAME SECTION AS FIGURE 12 BUT UNDER POLARIZED LIGHT AND THROUGH CROSSED NICOLS

Note the strong double refraction indicated by the light band from the clay layer on the surface of the aggregate.

FIG. 14. HORIZONTAL THIN SECTION OF FOSSIL B HORIZON AT A DEPTH OF 40 INCHES IN SODUS LOAM, PROFILE 5, AT 75 × MAGNIFICATION

Note the small clayey bodies near the bottom of the picture.

FIG. 15. SAME SLIDE AS FIGURE 16 BUT UNDER POLARIZED LIGHT AND THROUGH CROSSED NICOLS

Note that the clays have the optical properties exhibited in figure 13 of the Ontario soil.

composed mainly of sands and silts. Their occurrence suggests that they may be remnants of larger concentrations, like those of the Ontario soils, which have been largely lost by processes operating inward from the surfaces of the aggre-

gates. Figure 16 is an enlargement of a section from the lowest part of the comparable horizon in one of the intergrades, and in this case the zones of clay concentration appear to be essentially like those of the Ontario soils. In this profile the upper part of the horizon had properties like those shown in figures 11, 14, and 15.

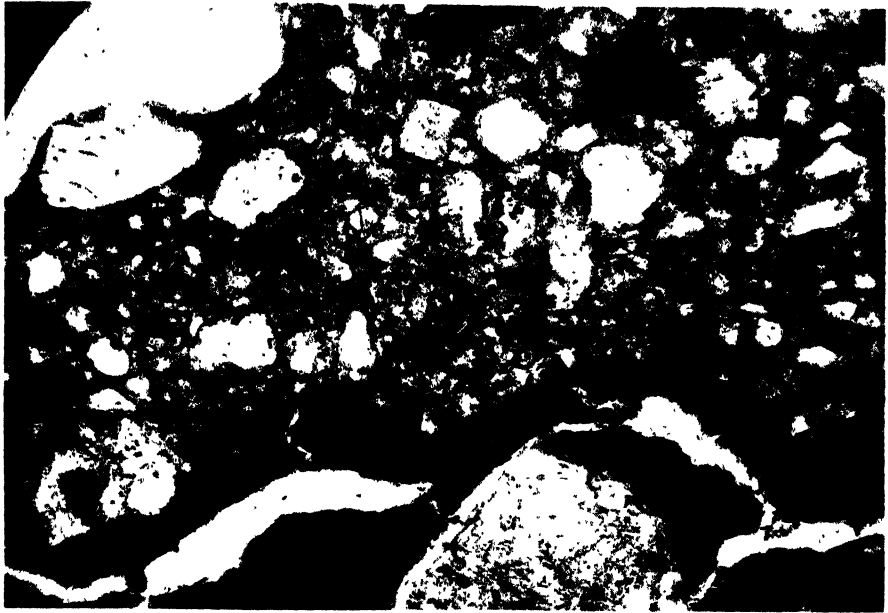


FIG. 16. VERTICAL THIN SECTION OF "FOSSIL" B HORIZON AT A DEPTH OF 50 INCHES IN SODUS INTERGRADE, PROFILE 4, AT 150 \times MAGNIFICATION

Note the clay accumulation and its very distinct layering

Parent material

Photomicrographs of the parent materials of the Ontario and Sodus soils are shown in figures 4 and 5, respectively. Stable aggregates are essentially absent. Clays, if present, occur uniformly mixed with the sand and silt fractions in both. The outstanding difference between the two figures is the presence of a high proportion of limestone and dolomite fragments in the parent material of the Ontario soil and the almost complete absence of calcareous rock fragments in the parent material of the Sodus soil.

DISCUSSION

The outstanding characteristic of gray-brown podzolic soils is the textural profile. The apparent loss of clays in the A₂ horizon and the apparent gain in the B may be accounted for in at least three possible ways:

1. Clays may migrate as sols in percolating waters from the A to the B, as has commonly been assumed (1, 2). Pallmann and others (11) have suggested that, in nearly neutral soils of

Switzerland comparable to the Ontario soils of this study, silicate clays may migrate downward with colloidal silica as a protective colloid.

2. Products of weathering from the A horizon may move downward in true solution and with weathering products from the B may be synthesized into silicate clays. Until the clays have been identified and possible sources investigated there is no reason to postulate synthesis rather than alteration as the source of clay in any horizon.

3. Removal of other constituents, such as calcium carbonate, from the B horizon might concentrate clays residual from the parent materials. Mickelson³ in mineralogical studies of the Miami series could account for the apparent clay accumulation in the B by loss of other constituents and postulated that the lower percentage of clays in the A was due to chemical decomposition.

The thin sections used in this study provide some evidence that the clays in the Ontario soils have accumulated in the B horizon from percolating water. The clay in the B horizon is not uniformly distributed throughout the horizon but is concentrated on aggregate surfaces (figs. 10 and 11). The occurrence of aggregates and pore spaces is undoubtedly at least partly the result of the localized concentration of clays, but if the clays were the weathering products of primary minerals originally in this part of the profile or were residual from clays originally present in the till, one would expect to find them more uniformly distributed throughout the horizon. Even differential weathering of the aggregate surfaces would not produce such uniformly clayey bodies. In addition, the layering and optical continuity of the clayey bodies (fig. 13) would be unlikely if the clays were residual from either clays or other minerals originally present in this part of the profile. The mode of occurrence and optical continuity both suggest that the clays have been deposited on the walls of channels through which percolating waters pass. Their ultimate origin is open to conjecture.

The micromorphology of the brown podzolic Sodus soils is strikingly different from that of the Ontario soils. The yellowish red coatings on primary particles in the topmost mineral horizon (fig. 9) have optical properties very much like those of thicker coatings in the B horizon of well-developed podzols. Although the modal Sodus profile has at most only an incipient *Bleicherde*, the presence of these thin films suggests that sesquioxides are being released much as they are in podzols. This would be expected under conditions of strong acidity such as exist in the solums of brown podzolic soils of New York. Oxide clays, therefore, appear to play a dominant role in the formation of brown podzolic soils, in contrast to the apparent dominance of silicate clays in the mobile fraction in gray-brown podzolic soils. This would suggest, as indicated by Cady (3), a very close relationship between the brown podzolic soils of New York and podzols, not only in morphology but also in soil-forming processes. The differences between the two soils as to morphology and process would appear to be mainly of degree and not of kind.

In the intergrades between the Ontario and the Sodus soils, the studies of thin sections provide evidence that a brown podzolic solum is developing in the upper horizons of a gray-brown podzolic soil. Occasional sesquioxide concretions

³ MICKELSON, G. A. Mineralogical composition of three soil types in Ohio with special reference to changes due to weathering as indicated by resistant heavy minerals. Unpublished thesis, Ohio State University. 1943.

and coatings were found in the A₂ horizon of Ontario loam, and these increase from the least acid to the most acid profiles. These coatings are responsible for the yellowish tinge of the upper part of the A₂ horizon of gray-brown podzolic soils in New York, as similar coatings are the source of the yellowish color of brown podzolic solums.

In the gray-brown podzolic profiles with strongly acid A₂ horizons, thin, light gray coatings extend from the A₂ horizon downward around the aggregates of the upper part of the B. These coatings consist mainly of silt- and sand-sized particles; clayey bodies occur inside the coatings in the position they would occupy if degradation of the aggregates were proceeding from the outside inward. This phenomenon becomes more distinct the higher the acidity of the upper part of the profile. In the two intergrades between the Ontario and the Sodus series, the gray coatings were thick and extended well into the B horizon, but the lowest part of the horizon was essentially the same as the B₂ horizon of the modal Ontario soils (fig. 16). In the modal Sodus profile, similar grayish material dominated a thick horizon below the normal brown podzolic solum (fig. 11). Under high magnification, however, small clayey bodies could be seen in the lowest part of this horizon also (fig. 14). The increase of grayish "leached" material and decrease of clay in these horizons is correlated with the degree of depletion of bases in the soils studied.

Drainage water in these regions is high in bases; it may be assumed, therefore, that bases are being depleted. The observed correlation of soil properties with differences of base status suggest that, as bases are depleted in gray-brown podzolic soils of New York, development of a brown podzolic soil proceeds with release of sesquioxides in the topmost horizon at the same time that the clayey B horizon degrades progressively from top to bottom.

SUMMARY

Thin sections of genetic horizons of six profiles, ranging from well-developed gray-brown podzolic to well-developed brown podzolic soils, were studied under the petrographic microscope. Biological activity in the topmost horizon was much greater in the gray-brown podzolic than in the brown podzolic soils. In the second horizon of the gray-brown podzolic soils, very thin yellowish brown coatings and concretions gave the horizon a yellowish tint. These coatings resembled thicker films that bind sand and silt particles together weakly in brown podzolic soils and appeared to be iron oxides. Strong concentrations of clays with a high degree of optical continuity were found in the B horizon of the gray-brown podzolic soils as thick coatings on the nuciform aggregates. Distinct evidence of destruction of comparable clay bodies was observed (a) in the topmost part of the B horizon of the modal gray-brown podzolic soil, (b) extending deeply into the B horizon of the intergrades, and (c) strongly expressed throughout the lower horizons of the well-developed brown podzolic soil. In the last profile these clayey remnants were visible only under very high magnification. These observations are interpreted as evidence that a brown podzolic solum will develop in a former gray-brown podzolic soil in central and western New York if bases are depleted.

ZUSAMMENFASSUNG

Der nordwestliche Teil des Staates New York ist grösstenteils mit eiszeitlichen Ablagerungen bedeckt. Drumlins sind häufig und sehr gut ausgebildet. Die auf solchen Drumlinmoränen vorkommenden Böden jener Gegend werden als "Ontario" bezeichnet, insofern sie neutral oder schwach sauer sind im Obergrund. Sie werden als "Sodus" klassifiziert im Falle stärkerer Podsolierung und Obergrund-Versauerung. Diese beiden Entwicklungsstufen sind Glieder verschiedener Bodentypen (Great soil groups). Ontario-Böden gehören zum "Gray-Brown Podzolic" Typ, mit starker Tonwanderung im Profil. Sodus-Böden werden in die "Brown Podzolic" Gruppe eingereiht; sie haben viel Ähnlichkeit mit stark podsolierten Braunerden.

Die vorliegende Studie zeigt, dass Ontario- und Sodus Böden verschiedene Stufen einer Entwicklungsreihe sind, die als Funktion fortschreitender Auswaschung der Erdalkalikarbonate zu verstehen ist. Als Beweis ist anzuführen, das ständige Vorkommen von fossilen Resten des (für Gray-Brown Podzolic Böden kennzeichnenden), dunkel-braunen Tonanreicherungs-Horizonts in den podsolierten Braunerden (Sodus-Böden).

Der dunkelbraune, tonreiche B-Horizont der Ontario-Böden wurde genauer mikro-morphologisch untersucht. Auf eine aktive Einfiltrierung der Tone in diesen Horizont wurde aus folgenden Feststellungen geschlossen: Die Tone sind besonders stark angereichert an den Krümeloberflächen und in Bodenhohlräumen, diese Tonakkumulationen zeigen deutliche Schichtung, ihre hohe Doppelbrechung im polarisierten Licht, lässt auf gute, räumliche Gerichtetheit der Einzelkristalle schliessen.

REFERENCES

- (1) BROWN, I. C. AND BYERS, H. G. 1938 Chemical and physical properties of certain soils developed from granitic materials in New England and the Piedmont, and of their colloids. U. S. Dept. Agr. Tech. Bul. 609
- (2) BROWN, I. C., AND THORP, J. 1942 Morphology and composition of some soils of the Miami family and the Miami catena. U. S. Dept. Agr. Tech. Bul. 834.
- (3) CADY, J. G. 1941 Soil analyses significant in forest soils investigations and methods of determination: III. *Soil Sci. Soc. Amer. Proc.* (1940) 5: 352-354.
- (4) CLINE, M. G. 1949 Profile studies of normal soils of New York: I. *Soil Sci.* 68: 259-272.
- (5) COILE, T. S. 1936 Soil samplers. *Soil Sci.* 42: 139-142.
- (6) FLINT, R. F. 1947 Glacial Geology and the Pleistocene Epoch. Wiley, New York.
- (7) FREI, E. 1947 Mikromorphologische Bodenuntersuchungen anhand von Dunnschliffen. *Mitt. Lebensmitt. u. Hyg., Eidg. Gsndhsamt.* [Switz.] 38. 138-143.
- (8) GILLETTE, T. 1940 Geology of the Clyde and Sodus Bay quadrangles, New York. N. Y. State Mus. Bul. 320.
- (9) MERRILL, F. J. H. 1901 Geologic map of New York. N. Y. State Mus., Albany.
- (10) MORDOFF, R. A. 1925 The climate of New York State. N. Y. (Cornell) Agr. Exp. Sta. Bul. 444.
- (11) PALLMANN, H., FREI, E., AND HAMDI, H. 1943 Die Filtrationsverlagerungen hochdisperser Verwitterungsprodukte im Bodenprofil einiger Glieder der schweizerischen Braunerdeserie. *Ber. Schweiz. Bot. Gesell.* 53A: 176-191.
- (12) U. S. Department of Agriculture. 1941 Yearbook of Agriculture, Climate and Man. Washington, D. C.

BOOKS

Corn and Corn Growing. Fifth Edition. by J. J. NEWLIN, EDGAR ANDERSON, AND EARL N. BRESSMAN. John Wiley and Sons, Inc., New York, 1949. Pp. 424, figs. 64. Price \$4.50.

The first edition of this book, prepared by Henry A. Wallace and Earl N. Bressman, was published in 1923. Since that date, highly important developments have taken place in corn growing, and this fifth edition is intended to bring the book up to date. The text covers the history and importance of the corn plant, its breeding and genetics, the classification of corn, the development of plant parts, the growing, harvesting, and feeding of corn, sweet, pop, and waxy corn, economic problems involved in corn production and in its selling price, corn-hog interrelationships, corn products and their uses, and corn statistics. A list of references is appended to each of the 28 chapters. The appendix contains a glossary of terms. The book has value not only as a textbook but also as a source of information for the individual farmer who is trying to produce high acre yields of this very valuable crop.

Farm Work Simplification. By LAWRENCE M. VAUGHAN AND LOWELL S. HARDIN. John Wiley and Sons, Inc., New York, 1949. Pp. 145, figs. 48. Price \$2.80.

Possibilities in saving steps and unnecessary work on the farm merit more consideration than has been given them. The authors of this book consider the problems involved and offer a number of interesting suggestions looking toward the simplification of farm tasks. The book was an outgrowth of deliberations of the work simplification committees of the American Farm Economic Association and the American Society of Agricultural Engineers, and these groups contributed to the thinking on the subject. The several chapters deal with what farm work simplification is, what savings can be made, principles of effective work, how results can be used, and research and training in work simplification. A list of available films and slides is appended. The book merits study on the part of those who farm, as well as those who teach the science and art of farming.

La Génétique des Sols. By ALBERT DEMOLON. Presses Universitaires de France, Paris, 1949. Pp. 134.

This pocket-sized, paper-bound volume presents a very interesting account of the development of our present concepts of soil genesis. Its five chapters deal with historic development, pedogenesis and types of soils, surveying and mapping, the soils of France, and applications of pedology. In addition to a number of interesting illustrations, the book contains generalized soil maps of Europe, by Palmann and Stremme, of Africa, by Marbut, and of the entire earth, by Glinka, Marbut, and Kellogg. The material is very attractively presented. This book would be a convenient one for the student of French to carry about in his pocket for use during spare periods.

Pedology. Second Edition. By JACOB S. JOFFE. Pedology Publications, New Brunswick, New Jersey, 1949. Pp. 662, plates 30. Price \$6.25.

This book is primarily a review, interpretation, and documentation of pedological science in Russia. The author is especially adept in this capacity in that he was born and raised in Russia and has complete command of the language. His contribution, therefore, is also one of translation from a tongue with which few American scientists have any very dependable working knowledge.

The text has been almost completely rewritten. The chapter on "The Soils of The United States" was omitted and one on "Soil Organic Matter" was added in its place. The text is divided into three parts: soil genesis, soil systematics—climatogenic soil types, and soil systematics—climatogenically subdued soil types. The presentation is greatly improved over that of the first edition and makes much more interesting reading. Every soil-plant scientist will want a copy at hand for ready reference. He will find himself very much indebted to the author for the many hours of painstaking work that went into its preparation.

Physics in the Modern World. By HENRY SEMAT. Rinehart & Co., Inc., New York, 1949. Pp. 434. Price \$5.

This book is designed for one-semester use with students in colleges of arts and social sciences who are not primarily concerned with the physical sciences but have need to know something of the methods employed therein. The material is presented in lucid and largely nontechnical form, with many well-chosen illustrations, including pictures of the most famous physicists of all time, accompanied by discussions of their contributions. The chapter headings include motion, force and motion, work and energy, fluids and motion, sources of radiant energy, utilizing light, communication, structure of the atom, and nuclear energy. The appendixes contain suggestions for teachers, a list of books for supplementary reading, a series of important tables of densities, specific heats, constants, atomic weights and others, a glossary of terms, and answers to the problems posed. The author is to be congratulated on having written an excellent book which should prove highly useful for the purpose for which it is intended.

The Production of Field Crops. Third Edition. By T. B. HUTCHESON, T. K. WOLFE, AND M. S. KIPPS. McGraw Hill Book Company, New York, 1948. Pp. 430, figs. 75. Price \$4.50.

Old material has been omitted or replaced, and many of the chapters have been almost completely rewritten in this third, revised edition. The book is divided into nine sections under the headings of general, cereal or grain crops, legumes for seed, forage crops, root crops, fiber crops, tubers, sugar plants, and stimulants (tobacco). These are subdivided into 36 chapters. The general part of the book deals with the history, economics, classification, and growing of field crops, including consideration of seed, fertilizer, lime, manure, tillage, harvesting, rotation, and weed control. The remainder of the book discusses

specific crops or groups of crops. At the end of each chapter is a list of references and of topics for discussion in class. By reason of their location and their experiences related thereto, the authors have been able to prepare what is perhaps the most widely useful text so far developed on this subject. The book merits a place on every agronomist's shelf.

Soil Fertility Diagnosis and Control. By CHARLES HENRY SPURWAY. Published by the author, East Lansing, Michigan, 1948. Pp. 176, Price (lithoprinted) \$3.50.

This book is a product of 40 years' study of soil fertility problems as related to field, garden, and greenhouse soils and crops. The subject is discussed under headings of introduction, crop production factors, physical soil factors, chemical soil factors, available fertility, nutrient requirements, soil fertility diagnosis, soil fertility control, and applications of soil fertility diagnosis. The appendix contains information on adjusting standard rates of application to small areas or volumes of soil and on fertilizer materials and rate of use. It also has a table for calculating pounds of fertilizer from pounds N, P_2O_5 , and K_2O . A great deal of careful thought and effort have gone into the writing of this book, which should prove highly useful to all those who have to do with making recommendations concerning liming, fertilizing, and manuring, with special reference to the more intensive systems of cropping. The type is a little too small for easy reading, but this means that the book contains more material than the number of pages would indicate.

Titans of the Soil. By EDWARD JEROME DIES. The University of North Carolina Press, Chapel Hill, 1949. Pp. 213, plates 18. Price \$3.50.

The author has chosen George Washington, Thomas Jefferson, Elkanah Watson, Eli Whitney, Henry Ellsworth, Edmund Ruffin, John Deere, Cyrus McCormick, Justin Morrell, Samuel Johnson, Wilbur Atwater, Seaman Knapp, Stephen Babcock, Theobald Smith, Mark Carleton, Harvey Wiley, and George Schull as the "great builders of agriculture." A full-page reproduction of a painting or photograph of each man is shown and a condensed account of his contribution to agriculture is given. Shorter statements on Abraham Lincoln, Horace Greeley, Luther Burbank, David Fairchild, Liberty Bailey, Cyril Hopkins, the Cokers, Henry Ford, and George Carver are appended. As these men pass in review, one is impressed by the remarkable developments in agriculture between the time when Washington was born, in 1732, and the day, in 1940, when the gold medal award was given to Shull for his work in developing hybrid corn. Thus our modern agriculture has come to its present high degree of efficiency in only a little more than two centuries. The book makes highly interesting reading.

Trace Elements in Food. By G. W. MONTER-WILLIAMS. John Wiley and Sons, Inc., New York, 1949. Pp. 511. Price \$6.

An excellent review of trace element literature, with special reference to nutrition and toxicology, this book covers Cu, Pb, Zn, Sn, As, Sb, Se, Fe, Ni,

Co, Mn, I, Br, F, B, Si, Al, Ag, Cd, Cr, Bi, Hg, Mo, V, Ti, In, Ba, and Sr. The last chapter touches on Li, Rb, Cs, Be, Zn, Ce, Ge, W, Tl, U, and rare-earth oxides. The arrangement of the elements in the book and the space devoted to each of them were determined largely by their relative significance as food constituents and their chemical relationships. For the first element, Cu, perhaps the best example, the chapter units are: copper as an essential element in plant and animal life (enzymes, haemoglobin, other biological processes, and haemocyanin), in the organs of the body, biochemical availability, absorption, excretion, and retention, minimum requirements, deficiency effects in cattle and sheep, pigmentation, toxicity, in soils and plants, in fungicides, corrosion by foods, in milk, cheese, butter, and ice cream, in relation to vitamins and fermentation and to haze in wines, in tomatoes and other foods, in relation to public health, methods of determination, and some 240 references. The author was formerly inspector of foods, local government board, and chemist in charge of food research laboratory of the Ministry of Health, London. The book fills a highly important need in the literature on this field of research.

The Use of Isotopes in Biology and Medicine. The University of Wisconsin Press, Madison, 1948. Pp. 445. Price (photolithographed) \$5.

During the week of September 10, 1947, leading physicists, chemists, and biologists reviewed recent developments in atomic physics at a conference in Madison, Wisconsin, and the major papers there presented are published in this volume. The contributors are Clarke, Urey, Seaborg, Aebersold, Nier, Kamen, Coryell, Melville, Wood, Sprinson, Bloch, Greenberg, Chaikoff, Hertz, Hamilton, Hall, Bale, Nickson, and Daniels. The several papers deal with the historical background, separation of stable isotopes, preparation of radioactive isotopes, recent developments, detection of stable isotopes, measurement of radioactivity, assay of radioactive isotopes in biological research, preparation of compounds containing isotopes, studies of metabolism of proteins, carbohydrates, lipids, and mineral elements, radioactive iodine, medical applications, therapeutic use of radiophosphorus, health hazards, international aspects, comments on developments in atomic energy, and subjects of panel discussions. A list of references is appended to each paper. This is a valuable reference book that should occupy an important place on the work table of those who are conducting researches in this field of study.

THE EDITORS

A PIEZOMETER METHOD FOR MEASURING PERMEABILITY OF SOIL IN SITU BELOW A WATER TABLE¹

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In a method proposed by Kirkham (6) for the measurement of the permeability of soil below a water table, a cylindrical tube was to be placed tightly in a hole of the same size and filled with water to a measured height above the water table. The rate of fall of the water level in the tube was then to be observed and the permeability determined by use of a formula based on Darcy's law. Frevert and Kirkham (4) first applied this method. To minimize puddling and compaction of the soil at the base of the tube, they found it desirable to use tubes as large as 8 inches in diameter. With the aid of special driving and soil-removing equipment, and by observing an inflow seepage rate rather than an outflow rate as originally proposed, they obtained reproducible results to depths up to 30 inches. At greater depths, because of the large size of pipe and limitations in the soil-removing equipment, the method appeared impractical.

Hooghoudt (5) measured soil permeability below a water table by drilling auger holes into the soil and observing therein the rate of rise of water, a method first used by Diserens (3). The formula used by Hooghoudt for converting observed measurements to permeability values was, however, based on certain simplifying assumptions. Kirkham and Van Bavel (7, 10) gave an exact theory and applied the result to permeability measurements on Iowa soils. Despite Hooghoudt's assumption, it turns out that his results were not far in error. In one practical case the error was only 10 per cent.

The auger-hole method has certain limitations. First, the permeability obtained is a sort of average value of the soil permeability over the depth of the hole. Secondly, variations of the permeability in the soil profile are not shown. (The effect of one layer might completely dominate.) Finally, for practical reasons, the method is limited to shallow depths.

To overcome limitations in the above methods, a new procedure utilizing pipes of small diameter (piezometers) has been developed. The method consists basically in measuring the rate of flow into a cavity at the base of an emptied piezometer (fig. 1).

Advantages of the method are: (a) the permeability can be determined, for practical purposes, to any depth; (b) the permeability of any layer in the soil can be measured; (c) the method is relatively quick, accurate, and simple. Like the methods referred to above, measurements are made on undisturbed soil *in situ*. It is the purpose of the present paper to describe this piezometer method and to report some field trials.

¹ Journal Paper No. J-1644, Iowa Agricultural Experiment Station, Ames, Iowa, Soils Subsection, Project 998.

FIELD PROCEDURE

After first removing a few square inches of surface sod at the location for measurement, a hole is augered to a depth of 6 inches. A pipe, sharpened at one end, is driven axially with light blows of a maul (to minimize soil compaction) into this hole to a depth of 5 inches. The auger hole is made with a soil auger the diameter of which is about $\frac{1}{8}$ inch less than the inside diameter of the pipe. The sod is removed to prevent balling of soil and roots on the pipe end. With the pipe end driven into the hole to a depth of 5 inches, the soil auger is inserted into the pipe and the soil removed to a depth 6 inches below the pipe bottom. The auger is removed and the pipe driven 5 inches deeper as before. This process is continued until the pipe end reaches the depth for measurement. The auger

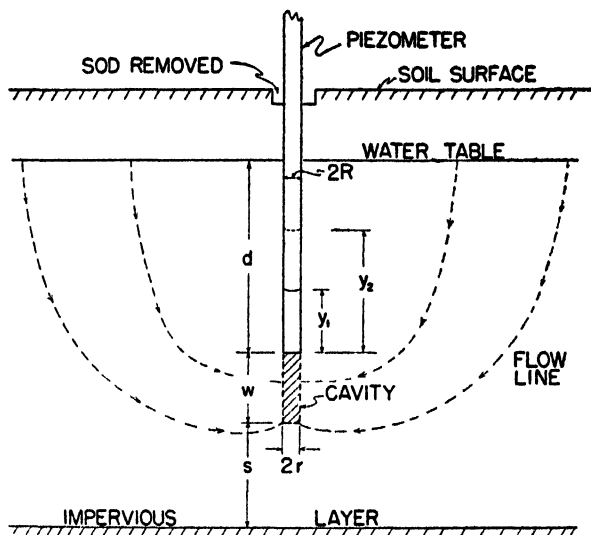


FIG. 1. DIAGRAM ILLUSTRATING THE PIEZOMETER METHOD OF PERMEABILITY MEASUREMENT

is then used to drill out a small cylindrical cavity at the pipe bottom. A 4-inch cavity has proved satisfactory. A stop may be fastened to the shaft of the auger to make contact with the top of the pipe when the proper depth hole is drilled.

The hose from a pump is then inserted into the pipe bottom, and water that seeps into the cavity is pumped out. The purpose of the pumping, which must sometimes be repeated a number of times, is to remove puddled soil from the walls of the cavity. The water seeping in flushes out the soil pores. After puddling effects have been minimized (which may be checked by reproducibility of results on an individual hole), the soil water is allowed to rise in the pipe and the rate of rise is determined with the aid of stop watches and an electric probe, as described by Van Bavel and Kirkham (10). In highly permeable prairie soils the equilibrium water level establishes itself in about 15 minutes; in tight clay soils, longer times are required. The observed data are finally reduced to standard units with the aid of an appropriate formula discussed later.

With regard to the time required for making field measurements, it is found that one man working in loam soil with 1-inch piezometers can install four pipes at 2, 3, and 4 feet; obtain readings at each of the depths; and remove the pipes all in 6 hours. On heavy clay soil the time is doubled. If two men, one unskilled, work, the number of readings in a given time can be doubled.

The pump is a small pitcher pump commonly found on farms and weighing about 13 pounds. Plastic garden hose $\frac{1}{4}$ inch outside diameter and $\frac{1}{8}$ inch inside diameter has been used. Thick-walled hose is needed, since in tight soils considerable suction is desirable for rapid removal of puddled material from the walls of the cavity. When high suction is applied, the hose is not inserted into the pipe but is connected to a tube passing through a rubber stopper inserted in the top of the pipe. The hose is connected into the pump through a pipe extending from the base of the pump to a level above the pumping cylinder. This manner of hose connection prevents the pump from losing priming water between operations. A suction of 0.75 atmosphere can be developed by the pitcher pump.

Ordinary iron pipe and thin-walled electrical conduit have been used. Sizes have ranged from about $\frac{3}{4}$ to 2 inches inside diameter. Electrical conduit has proved satisfactory for depths up to 4 feet. This conduit is commercially available in 10-foot lengths at inside diameters of 0.5, 0.75, 1.00, 1.25, 1.50, and 2.00 inches. The conduit is light, strong, and resists corrosion.

The electric probe has consisted of a round $\frac{1}{2}$ -inch wooden rod graduated in inches. A wire embedded in, and with end protruding from, the end of the rod is connected in series with a limiting resistor, a milliammeter, and a 33-volt hearing-aid battery. The other side of the battery is connected to the pipe. When the wire in the rod touches the water surface the electric circuit is completed, causing the milliammeter to deflect. To keep the end of the rod, and hence the probe wire, from touching the walls of the pipe, the rod is tapered to a point. Care is taken to keep the probe dry, since the presence of a thin film of water may cause the milliammeter to deflect appreciably. The probe may be set and held at a specified depth by means of a collar attachment which fits on the top of the pipe. This same attachment serves as a mount for a horizontal panel on which the milliammeter, resistor, and battery are mounted. The panel also serves as a table for holding a data book and stop watches.

At depths greater than 5 feet a sounder device as developed by Christiansen (1) should prove more satisfactory than the probe described here. After measurements are completed, piezometers are removed with a modified Veihmeyer soil tube jack.² The modification consists of making a special grip for each size pipe. The yoke and rollers of the jack-assembly are standard. The jack rollers are removed when large size pipes are pulled. No difficulty has been met in pulling pipes up to 2-inch size at 4-foot depth.

CONVERSION OF OBSERVED DATA TO SOIL PERMEABILITY

The A-function

The general solution for the problem of flow into a cylindrical hole, with impervious walls and with open end below a water table, was given by Kirkham (6). The expression obtained for the permeability may be written in the form³ (fig. 1).

$$K = \frac{\pi R^2 [\ln (d - y_1) / (d - y_2)]}{A(t_2 - t_1)} \quad (1)$$

¹ Manufactured by the Robert McNairn Machine Works, Inc., 1431 2nd St., Sacramento 14, Calif.

² The formula as presented here differs from that originally given in that the viscosity of the soil water, and density, and the acceleration of gravity are lumped into the permea-

where, K = soil permeability (quantity of water discharging in unit time through a column of soil of unit length and unit cross section, the ends of which are at unit difference in hydraulic heads), R = inside radius of pipe, \ln = natural logarithm, d = depth of pipe below water table, y_1 = depth below water table of water in pipe of time t_1 , y_2 = depth below water table of water in pipe at time t_2 , $t_2 - t_1$ = time required for water to rise from y_1 to y_2 , A = a function of the geometry of the flow system having the physical dimensions of length.

The units used in equation (1) are: K , inches ³/inches ²/day = inches/day; R , inches; d , y_1 , y_2 , inches; A , inches; $(t_2 - t_1)$, days.

The quantity A may be called the A -function. Physically A is a sort of conductance; it is the amount of water which will flow into the cavity in unit time if the soil permeability is unity and a unit difference of hydraulic head exists between points in the soil at the water table and points in the soil over the walls of the cavity. The A -function is the only quantity in equation (1) which can not be readily measured or otherwise obtained. In the present case (fig. 1) A is a function of the pipe depth d below the water table; of the outside radius of pipe, which may be taken equal to the inside radius R ; of the cavity radius r ; of the cavity length w ; and of the distance s from the lower end of the cavity to an impervious layer. One may not use r for R in the numerator of the right hand side of equation (1), since a small error in R introduces a larger error in R^2 and hence in K .

The A -function for use in equation (1) is evaluated by means of an electric analogue of the groundwater problem⁴ (4). The electrolytic tank is a stock-watering tank 68 inches in diameter and 20 inches deep, the bottom of which is lined with 26-gauge copper sheet. The electrolyte is tap water. The copper bottom simulates the water table; the water-air surface, the impervious layer; a dielectric rod, the piezometer; a right, cylindrical, copper electrode attached to the base of the dielectric rod, the cavity. The dimensions of the dielectric rod and the attached electrode are in the same proportions as are the dimensions d and $2r$ in the field. The A -function is computed from the formula

$$A = \frac{r}{r_m} \cdot \frac{1}{\sigma\Omega} \quad (2)$$

where, r = radius of the soil cavity, r_m = radius of cylindrical electrode, σ = specific conductivity of the tank electrolyte, Ω = electrical resistance between the cylindrical electrode and the copper tank bottom. A noninductive Wheatstone bridge was used for measuring Ω . A 500-cycle AC current at 6 volts was used for power supply, and ear phones were used for balance detection.

In equation (2), $(V_2 - V_1)/I$ was originally given instead of Ω . In the electric analogue V_2 (volts) would correspond to the hydraulic head in the soil at the

bility constant. Also, the quantities in the argument of the logarithm are reversed to account for inward seepage rather than outward seepage as originally described.

⁴ FREVERT, R. K. Development of a three-dimensional electric analogue with application to field measurement of soil permeability below the water table. 1948 [Unpublished doctorate thesis, copy on file Iowa State College Library, Ames.]

water table; V_1 , at the cavity; and I (amperes) to the quantity of water flowing in unit time into the cavity.

Laboratory results

Figure 2 shows the variation of the A -function with diameter of cavity for a 4-inch long cavity. This figure may be considered valid only if $d \gg w$, $s \gg w$; but is approximately valid, as indicated below, for other values of d and s .

Since the A -function is proportional to the dimensions of the cavity⁵, the A -function for other lengths may be computed from figure 2. This is shown in the following example: The A -function for a cavity 6 inches long and 2 inches in diameter is desired. A cavity 4 inches long to be in the same proportion must have a diameter of 1.33 inches. The value of A -function for a cavity 4 inches long and 1.33 inches in diameter is read from figure 2 to be 14.0 inches. The value, then, for the cavity 6 inches long and 2 inches in diameter is $(6/4) \times 14.0$ inches = 21.0 inches.

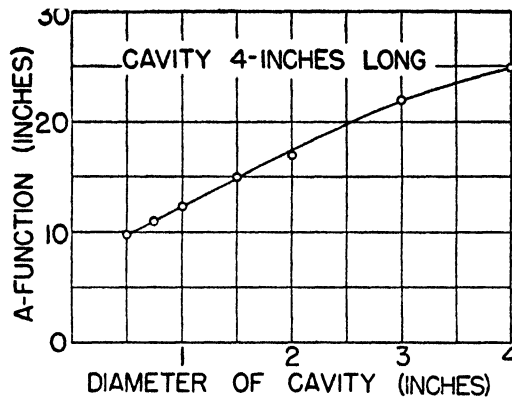


FIG. 2. VARIATION OF A -FUNCTION WITH DIAMETER FOR A CAVITY 4 INCHES LONG
For values of s and d see text

Figure 3 shows the variation of the A -function with length of cavity for a cavity 1 inch in diameter. Figure 3 may be used like figure 2 to compute A -values for cavities of other dimensions than those given on the graph. Thus, the A -function for a cavity 2 inches in diameter and 4 inches long is obtained as follows: For a cavity 1 inch in diameter to be in the same proportions it must have a length of 2 inches, and the A -function reading from figure 3 would be 8.5 inches. Since the cavity 2 inches in diameter and 4 inches long has dimensions which are twice those of the 1 by 2 cavity, the A -function would be $2 \times 8.5 = 17.0$, in agreement with the same value used from figure 2.

⁵ Kirkham (6, p. 62) has proved that doubling the dimensions of a flow system will double the A -function; but we have shown (cf. fig. 4) that when d and s are large compared to w , the value of the A -function is independent of d and s . Therefore, doubling the dimensions of the cavity doubles the value of the A -function, regardless of d and s . This line of reasoning is in agreement with the concept in the theory of electricity of an electrode in an infinite medium having a resistance which depends on its size only. (See Sir James Jeans, *The Mathematical Theory of Electricity and Magnetism*, ed. 5, Cambridge, 1933, p. 352.)

Figure 4 shows how the A -function varies with d (or with s) when $w = 4$ inches, $2r = 1$ inch, and $s + w + d = 24.5$ inches. This curve brings out the important fact that, if d and s are both large compared to w , the A -function varies inappreciably with d and s . Examination of this curve shows that the value of the A -function when obtained from figure 2 or 3 will be correct to better than about ± 8 per cent if $d \geq w$ and $s \geq \frac{1}{2} w$; and that the values will be correct to better than about ± 4 per cent if $d \geq 2w$, $s \geq 2w$. If $s = 0$ and $d \gg w$, the value of the

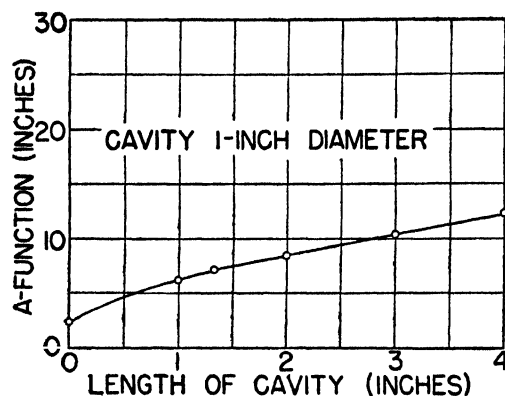


FIG. 3. VARIATION OF A -FUNCTION WITH LENGTH FOR A CAVITY 1 INCH IN DIAMETER
For values of s and d see text

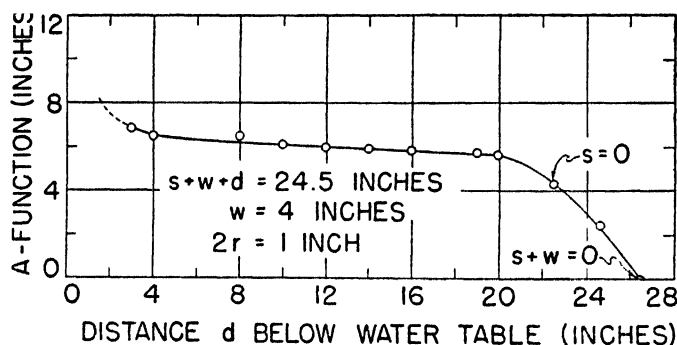


FIG. 4. VARIATION OF A -FUNCTION WITH s , FOR A CAVITY 4 INCHES LONG AND 1 INCH IN DIAMETER

A -function will be about 25 per cent too large when obtained from figure 2 or 3. The curve is relatively flat between $d = w$ and $s = \frac{1}{2} w$. It is from this portion of the curve that values were obtained for figures 2 and 3.

Results of field tests

Results of the field tests are summarized for four sites in table 1. The locations, except site 3, are on highly permeable prairie soils. At sites 1 and 2, the permeability of the soil, although a silty clay loam, was as high as that of a medium sand (9, p. 113). At site 4, readings were made with 2- and 1-inch diameter pipes at the 3-foot depth. The essential equality of the results 132 ± 68

and 124 ± 40 inches per day is considered a satisfactory check on the consistency of the method. In considering the deviations ± 68 , ± 40 and other deviations in table 1, it should be remembered that measurements of soil permeability by common methods often deviate more than 1,000 per cent (2).

In addition to the tabulated tests, trials were made on a glacial soil, a lacustrine soil, and on soil by an artificial lake. On these soils there were variations of 100 per cent or more in the permeability values. The variations are attributed not to errors in the method but to large local variations in the soil. Examination of the profiles revealed sand pockets and sand layers separated by clay often

TABLE 1
Permeability measurements with piezometers

SITE NUMBER* AND SOIL	INSIDE PIPE DI- AMETER	DEPTH OF WATER TABLE	DEPTH OF SAMPLE†	PERMEABILITY						
				Pipe 1	Pipe 2	Pipe 3	Pipe 4	Pipe 5	Pipe 6	Average
	in.	ft.	ft.	in./day	in./day	in./day	in./day	in./day	in./day	in./day
1 Webster silty clay loam	0.756	1.0	2	725	514	586	648			618 \pm 90
	0.756	1.0	3	1150	784	1222	1069			1056 \pm 192
	0.756	1.0	4	1144	1569	1355	1081			1287 \pm 221
2 Webster silt loam	1.50	1.1	2	788	532	622	860	767	748	728 \pm 116
	1.50	1.1	3	878	1140	888	955	878	813	925 \pm 114
	1.50	1.1	4	840	810	814	862	1218	1150	949 \pm 207
3 Luton clay (not typical)	1.0	0.6	3	1.79	1.78	1.57	1.92	1.92	1.97	1.82 \pm 0.147
	1.0	0.6	4	61.8	64.2	61.8				62.6 \pm 1.3
4 Marion silty clay loam	2.0	0.4	2	159	153	103	95			127 \pm 33
	2.0	0.4	3	232	103	114	78			132 \pm 68
	1.0	0.4	3	134	159	80				124 \pm 40

* The locations, except site 3, are on highly permeable prairie soils.

† From surface of soil to top of cavity.

only a few inches apart. Variations on the bank of the artificial lake can be accounted for by disturbances made during construction of the lake.

DISCUSSION

Effect of soil stratification

Strictly speaking, if the soil consists of stratified layers, the A-function depends upon the soil permeability in each of the layers, and upon the dimensions of the layers, as well as the dimensions of the cavity. If, however, the distance between a layer and the cavity is not greater than its length (and excluding any completely impermeable layer above the cavity), the effect of these layers, regardless of their permeability, will be small. This conclusion was verified by simulating the following two extreme cases in the model tank:

(A) With $d = 1$ foot, $w = 4$ inches, $2r = 1$ inch, and $s = 1.5$ feet an impermeable layer 1 inch thick and 4 feet in diameter was placed in the "soil" 4 inches above, and coaxially with the cavity. The A-function was measured and found to be reduced 11.5 per cent from

the value without the impermeable layer. The diameter of the impermeable layer was then increased to 8 feet and the A -function measurement made again. Its value remained essentially the same.

(B) With d , $2r$, and s as in (A), a layer of "coarse gravel" 9 square feet in area and 4 inches thick was placed in the "soil," with the lower surface of "gravel" 4 inches above the top of the cavity. The A -function was measured and found to have increased 6 per cent with respect to the value with no gravel.

In these experiments the impermeable layer was simulated by a disk of shellacked plywood, and the "gravel," by copper sheets bolted together by conducting screws. The removal of the homogeneous soil to make way for the "impermeable material" or for the "gravel" was accomplished by displacing electrolyte in the tank as the plywood and copper sheets were put in position.

Another check on the proposition that only the soil in a relatively small region about the cavity contributes principally to the soil permeability was obtained

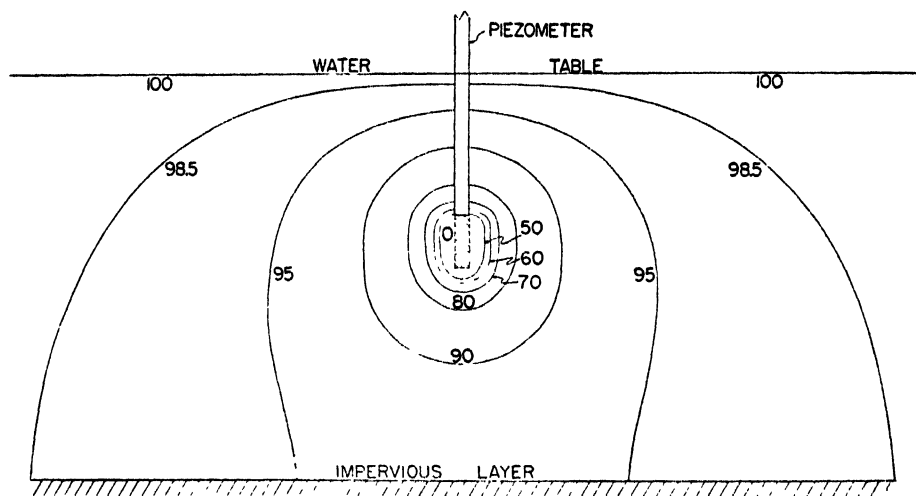


FIG. 5. EQUIPOTENTIAL CURVES FOR A PIEZOMETER CAVITY

by determining (with the apparatus developed by Frevert) the equipotential surfaces about the "cavity," as shown in figure 5. The value 100 is assigned as the potential (hydraulic head) at the surface of the "soil" and the value zero at the "cavity." The figure shows that 80 per cent of the hydraulic head is dissipated in the soil within a distance of 1 cavity length from the cavity and about 90 per cent within 2 cavity lengths. Soil outside the 80 and 90 rings thus contributes little to the flow and hence to the A -function and to the value of K .

Effects of rocks and channels

The effect of the proximity to the cavity of rocks and channels was investigated with the model. Pieces of dielectric material were used to simulate rocks; copper strips, cracks; and copper wire, wormholes. If the "cracks" and "worm holes" were not continuous from the cavity to the soil surface, their effect was generally small. The presence of rocks near the cavity had little effect on the A -function.

The effect of rocks and channels has also been studied by Frevert and Kirkham (4), the results found being essentially as in the present investigation.

Leakage along the walls of the piezometer may be serious in some soils, and where it occurs the values obtained for the permeability will be too high. If the color of the soil above the cavity is different from that of the soil about the cavity, as is often the case, any leakage could be detected by observing the color of the suspended material pumped from the cavity. No leakage along the piezometer walls has been encountered in tests made so far.

The first trials of the piezometer method were made by driving the piezometers to the desired depth, with no preliminary augering. Then, by repeatedly flushing out the hole over a period of 2 weeks, it was found that the permeability continued to increase until it reached a constant, but somewhat lower, value than the value obtained by installing the tubes with augering. The constant value, except in tight soils, is reached much sooner if augering is used. In tight soils, high in clay content considerable pumping of the cavity is required, despite installation with augering.

The method described in this paper does not distinguish the vertical and horizontal permeability as found in anisotropic soils. In such soils, the permeability as measured will be an average value. The method may fail in a sandy soil because the cavity may fill with sand. This might be prevented by use of a cavity of zero length, or the difficulty might be obviated by use of a piezometer the lower 4 inches of which are perforated. In the latter case, if the perforations are sufficiently dense [as is apparent from an investigation of Muskat (8)], the same A -function as for an open cavity may be used.

SUMMARY

A method of measuring soil permeability in the field below a water table has been developed.

Pipes are driven into the soil below a water table; the soil is augered out of the pipe, and the rate of rise of the water in the pipes is measured. The soil permeability is then calculated from this rate of rise by means of an appropriate formula.

Certain geometric constants occur in the permeability formula. These constants are determined in the laboratory with a three-dimensional electrical analogue of the ground-water flow problem.

This method has been tried on several Iowa soils with satisfactory results.

REFERENCES

- (1) CHRISTIANSEN, J. E. 1943 Ground-water studies in relation to drainage. *Agr. Engin.* 24: 339-342.
- (2) CHRISTIANSEN, J. E. 1944 Effect of trapped air on soil permeability. *Soil Sci.* 58: 355-365.
- (3) DISERENS, E. 1934 Beitrag zur Bestimmung der Durchlässigkeit des Bodens in natürlicher Bodenlagerung. *Schweiz. Landw. Monatsh.* 12: 188-198, 204-212.
- (4) FREVERT, R. K., AND KIRKHAM, D. 1949 A field method of measuring the permeability of soil below a water table. *Proc. Highway Res. Bd.* (1948) 28: 433-443.
- (5) HOOCHOUDT, S. B. 1936 Bijdragen tot de kennis van eenige natuurkundige grootheden van den grond, no. 4. *Verslag Landbouwk. Onderzoek.* 42 (13) B: 449-541.

- (6) KIRKHAM, D. 1946 Proposed method for field measurement of permeability of soil below the water table. *Soil Sci. Soc. Amer. Proc.* (1945) 10: 58-68.
- (7) KIRKHAM, D., AND VAN BAVEL, C. H. M. Theory of seepage into auger holes. *Soil Sci. Soc. Amer. Proc.* (1948) 13 (in press).
- (8) MUSKAT, M. 1942 The effect of casing perforations on well productivity. Amer. Inst. Mining and Metall. Engin. Tech. Pub. 1528.
- (9) MUSKAT, M. 1946 The Flow of Homogeneous Fluids. Edwards Bros., Ann Arbor, Mich.
- (10) VAN BAVEL, C. H. M., AND KIRKHAM, D. Field measurement of soil permeability using auger holes. *Soil Sci. Soc. Amer. Proc.* (1948) 13 (in press).

PRESSURE POTENTIAL OF WATER MOVING DOWNWARD INTO SOIL¹

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Two stages in the downward movement of water into soil are more or less limiting with respect to the ready translocation of water applied at the surface. The first occurs while water continues to be applied, and the second is reached after rapid drainage has ceased, when the soil is said to be at field capacity. Bodman and Colman (1) have studied the pressure potential of water in uniform columns of soil during the first of these two stages. They found that water passed through an extending "transmission" zone into an advancing "wetting" zone in which water content and pressure potential decreased with depth toward the advancing wet front. Within the transmission zone, water content and pressure potential remained almost constant at any particular depth and were of a similar magnitude at all depths except near the surface. While the surface was being kept flooded with water, the pressure potential in the transmission zone had a constant value of about -3×10^4 ergs/gm. in the two soils investigated.

In the present work, the pressure (or capillary) potential has been determined during downward entry into uniform soil under field and laboratory conditions, of water applied by flood and spray methods. In the latter case the effect of rate of application has been investigated. The trend in values of pressure potential following the cessation of water application has also been noted, and a range of values corresponding to field capacity obtained.

METHODS

Four soils, some physical properties of which are given in table 1, were used during these investigations. The field trials were conducted on Winkie sand at a site near Loxton, South Australia, where there was a relatively uniform profile to a depth of 4 feet. For the laboratory measurements, samples of a sand, a loam, and a clay were obtained near Adelaide, South Australia. The sand came from a dune, the loam from the surface horizon of Urrbrae loam in the red-brown earth group, and the clay from the surface horizon of a soil known locally as "Bay of Biscay." The loam sample had a high content of fine sand and a moderate content of silt and could have been described equally well as a silt loam.

Different rates of entry and conditions of water application were obtained in the field with spray and ring infiltrometers. Pressure potential was measured with tensiometers at depths of 15 cm. and 30 cm. at the centers of the test plots. The spray infiltrometer was a modified form of the North Fork infiltrometer (10) with a test plot measuring 4 feet by 1 foot in the center of a total sprayed area

¹ The work described in this paper was carried out as part of the research program of the Division of Soils, Commonwealth Scientific and Industrial Research Organization, Australia, at the Waite Institute, Adelaide, South Australia.

8 feet by 4 feet. The ring infiltrometer consisted of a flooded test plot, 1 foot in diameter, on which water was maintained to a depth of about 0.5 inch by a Mariotte tube.

A 1-inch screw auger was used in the field to excavate the soil for embedding the tensiometers. The soil was then packed back firmly to minimize the possibility of excess water flow through the disturbed soil. Soil was carefully packed around the tensiometers to ensure a good contact. Because of the sandy nature of this soil its replacement was a comparatively simple operation. The initial water content for the Winkie sand was 4.6, 4.9, and 2.6 per cent at depths of 15, 30, and 60 cm. respectively. Below 60 cm. the soil was dry to a great depth.

Records were kept of the pressure potential during three ring infiltrometer trials and during spray infiltrometer trials at three different rates of application. In the first of these spray trials, water was applied in excess of the infiltration capacity so that run-off occurred throughout. The minimum infiltration capacity

TABLE 1
Physical properties of soils to which water was applied

	WINKIE SAND*	SAND	LOAM	CLAY
Coarse sand (2 -0.2 mm.) per cent	44	65	5	3
Fine sand (0.2 -0.02 mm.) per cent	48	29	49	23
Silt (0.02-0.002 mm.) per cent	0	2	28	16
Clay (<0.002 mm.) per cent	7	4	17	57
Moisture equivalent per cent	3.9	3.2	19.5	46.0
Air-dry water content per cent	0.8	0.3	2.5	9.3
Apparent density gm./cc.		1.55	1.38	1.22
Minimum infiltration capacity . . . inches/hour	7.5	10.5	0.7	0.1

* Sample taken from a depth of 0 to 24 inches.

for the Winkie sand (table 1) was measured during this spray trial as the relatively steady rate of infiltration reached after water had been applied for about 15 minutes. In the second and third spray trials respectively, water was applied at one half and one quarter of this rate.

All the trials were continued long enough to provide steady readings of pressure potential at both depths. The water was then cut off, the test plots were covered, and continuous records were kept during drainage. Finally, when rapid changes in pressure potential had ceased (approximately 24 hours of draining for these sites), the tensiometers were removed and samples were taken at the two depths for measurement of water content.

The soils used in the laboratory method were air-dried and broken up to pass a $\frac{1}{4}$ -inch sieve. They were packed in a metal cylinder 15 cm. in diameter and 123 cm. long. The base of the soil column was seated upon a wire mesh which was soldered across the container 5 cm. above the lower end. Holes 1 cm. in diameter were drilled in the wall of the container, for insertion of the tensiometers and for water content sampling, at depths of 5 cm., 10 cm., and then at regular intervals

of 10 cm. down to 100 cm. below the position for the soil surface. The packing procedure consisted of adding soil by pouring with a circular motion, in layers about 10 cm. thick. Further settling was induced by tapping around the full circumference of the container with a wooden mallet. The apparent density of each added layer was determined by weighing the container and contents before and after each addition and by measuring the depth of the added layer. It was found to be a simple procedure to bring the soil up to the required density by tapping. The apparent density of the complete column 114 cm. in length was calculated after packing and was found to be in close agreement with the value adopted for each layer. The tensiometers were inserted during packing of the container to ensure good contact with the soil.

To prevent unnecessary deterioration of the surface structure of the soil when water was being applied, a protective layer of coarse sand about 2 mm. thick was placed on the surface. This sand layer also aided even distribution of water over the soil surface under limited rates of application. Water was applied by flood and spray methods. In the flood method a constant head of 1 cm. of water was maintained on the soil surface by a Mariotte tube. The minimum infiltration capacity for the laboratory columns given in table 1 was measured during these flood trials and was taken as the relatively steady rate of entry noted after infiltration had been in progress for some time. In the spray trials, water was applied to both the sand and loam columns at rates of 1, $\frac{1}{2}$, and $\frac{1}{4}$ times the values obtained in this way. For the clay, only one spray rate, equivalent to the minimum infiltration capacity, was used because of the difficulty of applying the lower rates accurately. The pressure potential during application was measured periodically from the beginning until water had penetrated at least 70 cm. deep.

Easy escape of entrapped air through the holes for the tensiometers and through the wire mesh at the base of the soil column excluded the possibility of this factor's having any influence upon infiltration. Some of the rates required for the spray applications were lower than could be obtained with a normal sprinkler. Consequently a method was devised of dripping water from a height of 30 cm. on a glass slide placed on the soil surface. The drops of water impinging on the glass were scattered in fine droplets over the whole surface. By varying the frequency of drops with a stopcock, it was possible to apply rates down to 0.1 inch per hour while still maintaining a fairly even distribution.

In the drainage trials a limited quantity of water was added at the soil surface by flood application so that dry soil would remain at the base of the column at the end of the drainage period. The surface was covered at the end of application to prevent evaporation. Records of pressure potential were kept from the beginning of the trial until rapid changes ceased. The tensiometers were then removed and samples taken from the different depths for water determinations.

Two types of tensiometers described by Marshall (6) were used. The field observations were made with porous cells about 8 cm. long and 2 cm. in diameter, and in the laboratory method a small tube type 0.6 cm. in diameter and 6 cm. long was used. Pressure potential was measured with mercury manometers with capillary tubing 2 mm. in diameter in the field trials and 1 mm. in diameter in

the laboratory. The mercury column was adjusted to a height of 30 cm. or more before water was applied. The correction for capillary depression in the manometer tubing was determined by direct measurement. No attempt was made to control temperature closely, but in both field and laboratory trials soil temperatures were in the neighborhood of 20°C.

TABLE 2
Pressure potential of water at depths of 15 and 30 cm. in Winkie sand

TYPE OF APPLICATION	DURING APPLICATION		AFTER DRAINAGE				
	Pressure potential		Period of drainage	Pressure potential		Water content	
	At 15 cm.	At 30 cm.		At 15 cm.	At 30 cm.	At 15 cm.	At 30 cm.
	$-g$ ergs/gm.	$-g$ ergs/gm.	hours	$-g$ ergs/gm.	$-g$ ergs/gm.	%	%
Ring infiltrometer							
Trial 1.....	-4	2	22	76	54	..	..
Trial 2.	5	8	17	76	68	.	..
Trial 3.	8	12	..	..	..	..	..
Trial 3, second application.....	8	13	..	..	..	..	..
Spray infiltrometer							
With run-off	1	-2		.	..	..	..
As above, second application....	5	0	26	*	63	..	.
$\frac{1}{4}$ minimum infiltration capacity.	6	6	16	66	62	9.3	10.7
$\frac{1}{4}$ minimum infiltration capacity.	4	2	..	..	..	.	..
As above, second application....	3	1	23	66	60	8.4	8.8
Mean.....	4	5	21	71	61	8.9	9.8

* Tensiometer out of order.

RESULTS

Pressure potential during application of water

The pressure potential within the transmission zone during application of water is given in table 2 for the field trials on Winkie sand. The second result shown for three of the trials was obtained during a second application following a brief period of drainage. The mean pressure potential for all trials at both depths was $-4g$ ergs/gm. where g is the acceleration due to gravity.² Results were somewhat erratic, but showed no consistent trend in pressure potential with respect to depth and no striking effect of either method or rate of application.

The results during application of water to uniform soil columns by flooding and by spraying at different rates are given in table 3. These values are the means of pressure potential recorded at each depth during application, after relatively constant values had been attained. The pressure potential within the transmission zone does not vary with depth for the sand or the loam. In the clay

² When the pressure potential is expressed in terms of $-g$ ergs/gm., the number (4 in this case) gives the tension as gm. cm./gm. or as the length in centimeters of an equivalent column of water.

column, however, there appears to be a slight trend toward decreasing values with depth. A considerable drop in pressure potential from zero at the surface occurred in the upper 5 cm. of the flooded sand and loam columns and in the upper 10 cm. of the two flooded clay columns. It is not possible to specify pressure potential at the surface of the sprayed columns.

The method of application (flood or spray) had no consistent effect on the pressure potential. There is a slight trend toward decreasing values as the spray

TABLE 3

Pressure potential at various depths in the transmission zone during the application of water to uniform columns of soil

SOIL	TYPE OF APPLICATION	PRESSURE POTENTIAL, IN—g ERGS/GM.										
		At 5 cm.	At 10 cm.	At 20 cm.	At 30 cm.	At 40 cm.	At 50 cm.	At 60 cm.	At 70 cm.	At 80 cm.	At 90 cm.	Mean
Sand	Flood	9	9	9	10	13	15	..	..	..	..	11
	{ minimum infiltration capacity	20	18	18	16	18	15	.	..	..	..	18
	{ minimum infiltration capacity	19	18	13	14	17	13	19	18	20	13	16
	{ ½ minimum infiltration capacity	24	23	23	24	27	26		.	..	..	24
	{ ¼ minimum infiltration capacity	24	26	22	24	20	18		..	..	..	22
	{ minimum infiltration capacity											
Loam	Flood	9	10	9	9	9	10	..	.	..	..	9
	Flood	10	10	10	10	11	9	12	6	10	8	10
	{ minimum infiltration capacity	7	12	9	8	8	5	6	4	4	8	7
	{ ½ minimum infiltration capacity	8	10	6	8	9	8	10	8	9	16	9
	{ ¼ minimum infiltration capacity	11	11	9	9	9	10	12	10	12	..	10
	{ minimum infiltration capacity											
Clay	Flood	6	13	17	19	20	..	..	..	..	..	15
	Flood	6	13	12	16	14	14	15	17	..	..	13
	Spray—minimum infiltration capacity	6	10	10	10	14	17	16	18	17	23	14

rate is decreased in the sand and loam columns. This trend was not observed in the sandy soil used in the field. The mean pressure potential for the three soils, including all methods and rates of application, is $-18g$ ergs/gm. for the sand, $-9g$ ergs/gm. for the loam, and $-14g$ ergs/gm. for the clay.

The present results for field and laboratory trials confirm the conclusion of Bodman and Colman (1) that below a depth of about 5 cm. there is no considerable gradient in pressure potential within the transmission zone during downward entry of water into uniform columns. The pressure potential is, however, of a higher order than the value of $-29g$ ergs/gm. reported by them, and much more variation was found between different soils. With the ingenious

technique developed by Bodman and Colman for studying downward movement, it was necessary to measure pressure potential indirectly from moisture samples. For the present purposes it was felt that a better measure could be obtained directly with tensiometers inserted at the appropriate levels. The tensiometers responded sufficiently rapidly to allow a number of steady readings to be made before a final value was assessed for each depth within the transmission zone. Since the initial setting from which the mercury column fell was equivalent to a much lower pressure potential than that noted by Bodman and Colman during transmission, the relatively high order of the final values cannot be due to lag in response. It may be due to real differences between the two groups of soils studied or to the different methods of measuring pressure potential.

Bodman and Colman suggested that further work might show that a single value of the pressure potential would be applicable to all uniform soils during water entry. Variations observed between different soils in the present work indicate that this is unlikely.

In general, the pressure potential in the transmission zone was found to be little affected by the rate or method of application of water. This result conforms with that obtained by Colman and Bodman (3) during investigations on the energy conditions existing in layered soils. With a silt-loam-sandy-loam sequence, where the rate of water supply to the sandy loam was governed by the permeability of the upper layer, they recorded pressure potentials in the sandy loam of the same order as those previously obtained with a uniform column of the same material.

The chief effect of lowering the application rate is a reduction in the rate of downward movement. At a given depth, the time required for establishment of the relatively constant pressure potentials recorded in table 3 varied inversely with the rate of application. For example the approximate times for spray rates equivalent to 1 , $\frac{1}{2}$, and $\frac{1}{4}$ of the minimum infiltration capacity were 55, 100, and 210 minutes in the sand and 11, 23, and 48 hours in the loam at the 40 cm. depth. Water penetrated more rapidly in the flooded columns than in the columns sprayed at a rate equivalent to the minimum infiltration capacity, since in the latter case the capacity of the soil to accept water was not fully satisfied in the early stages of the application. The comparable times for the two types of application were respectively 30 and 55 minutes in the sand, 8 and 11 hours in the loam, 6 and 9 days in the clay columns. From the time elapsing before tensiometers at a given depth began to react, it was noted in a limited number of observations that the rate of advance of the wet front was affected in a similar way by the rate of application. With the direct method used for measuring pressure potential, it was not practicable to assess other conditions within the wetting zone where pressure potential changes relatively rapidly with time.

Pressure potentials during drainage

The trend in pressure potential, following the disappearance of water from the surface after application had ceased, was determined in additional columns of soil and, under field conditions, in Winkie sand.

The columns were wetted by flood applications to a depth which would allow a dry zone to persist at the base of each during the desired period of drainage. Changes occurring in the sand, loam, and clay columns with increasing periods of drainage are shown in figures 1, 2, and 3 respectively. After water addition ceased, the transmission zone became a drainage zone below which the wetting zone extended as before down to the wet front. Within this drainage zone, the pressure potential at a given depth decreased with time. This distinguishes it

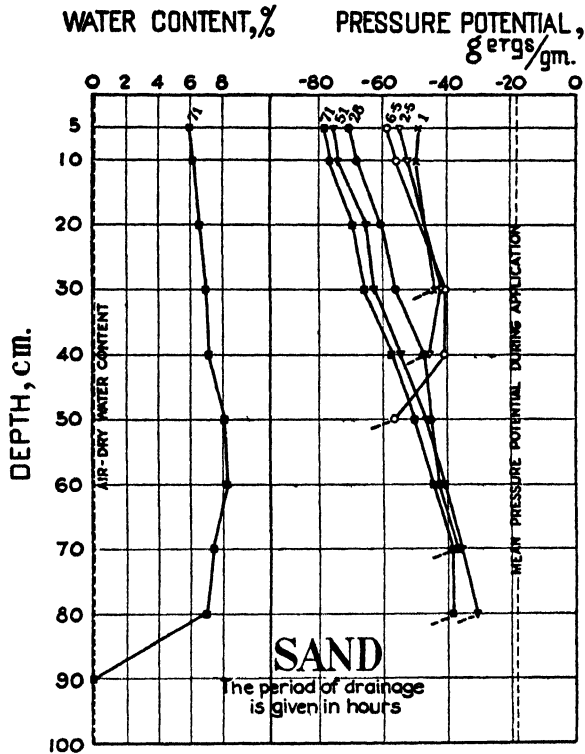


FIG. 1. PRESSURE POTENTIAL OF WATER AND WATER CONTENT OF SOIL DURING DRAINAGE OF SAND COLUMN

from the wetting zone in which the pressure potential increases at a given depth (until such time as the drainage zone extends to that depth.)

The rate of decrease of pressure potential in the drainage zone varied with depth and in general was greatest toward the surface. After about 24 hours, a gradient had developed with respect to depth which was relatively uniform at all depths and which was subsequently changed little during further drainage. This gradient had a value of $-0.6g$ dynes/gm. in both the sand and loam columns, the upward direction being taken as positive according to convention. In the clay column (fig. 3), the pressure potential changed more slowly with time at all depths. A gradient of $-0.2g$ dynes/gm. was developed after 48 hours of drainage and continued almost constant until the conclusion of the trial after 168 hours.

The same tensiometers were used in the same order in all columns. The tensiometer at the 20 cm. depth was consistently slow in reaction. The points obtained from it have been included for completeness, except those for the shortest drainage periods, which were obviously irrelevant.

Pressure potential was also measured at two depths during the drainage of Winkie sand. Soon after the supply of water had ceased, the manometers began to indicate a decreasing pressure potential. Significant changes in readings occurred within 2 minutes, the rate of change at the upper (15 cm.) level being

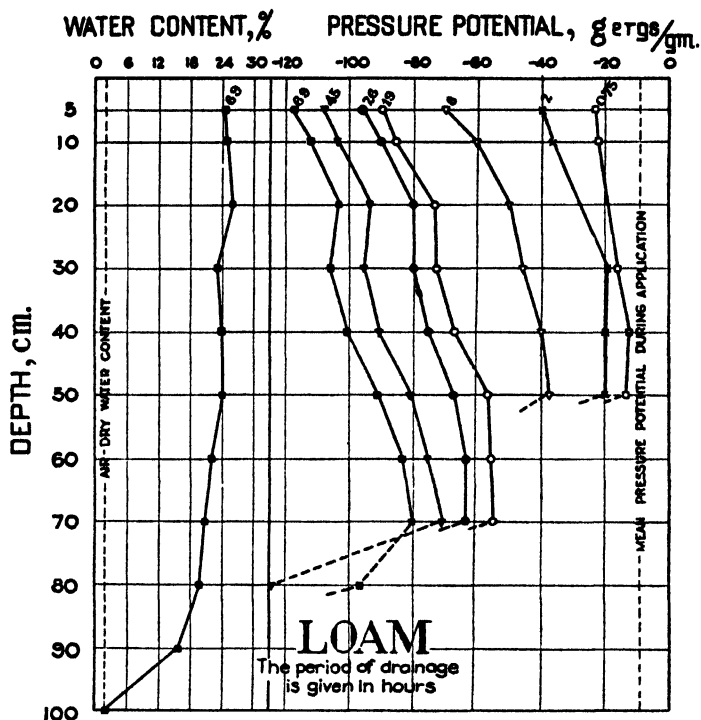


FIG. 2. PRESSURE POTENTIAL OF WATER AND WATER CONTENT OF SOIL DURING DRAINAGE OF LOAM COLUMN

greater than that at the lower (30 cm.). By the time drainage had proceeded for the periods indicated in table 2, the readings had become relatively steady and the soil was considered to be at field capacity. As in the columns, the pressure potential at the greater depth exceeded that nearer the surface. A similar relation is also evident in four out of five sets of results reported earlier (5) for Winkie sand at another locality at depths of 45 and 90 cm. when the soil was considered to be at field capacity. The gradients in pressure potential at both localities are variable, since each calculation of gradient depends on readings of single tensiometers at two depths only. The means are $-0.65g$ and $-0.2g$ dynes/gm. for the present and earlier data respectively.

These results show that in virtually all cases examined the pressure potential

increased with depth within the drainage zone after any period of drainage of uniform soil up to that equivalent to the attainment of field capacity. After drainage had proceeded sufficiently long and the pressure potential no longer changed rapidly, the gradient became relatively uniform at all depths and ranged in value between $-0.2g$ and $-0.6g$ dynes/gm. in different soils. After this stage of drainage (probably equivalent to field capacity) had been reached, the gradient in the columns did not change appreciably with additional drainage.

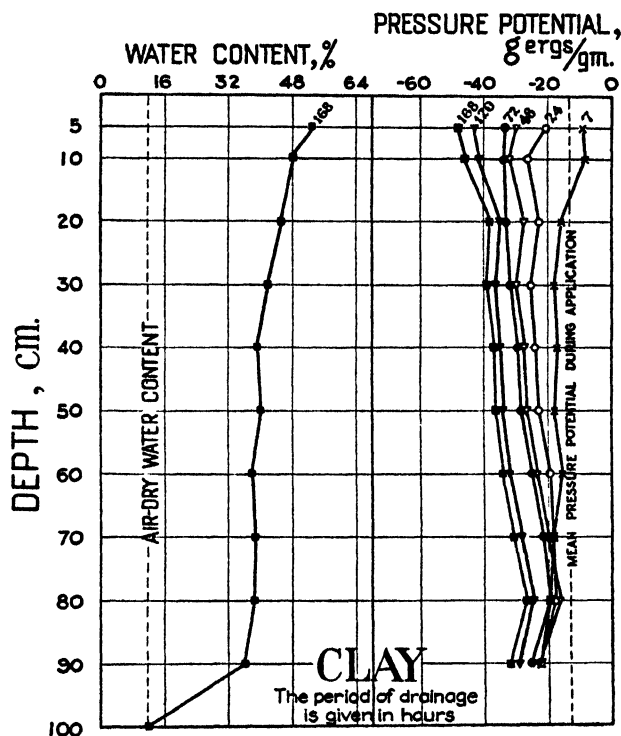


FIG. 3. PRESSURE POTENTIAL OF WATER AND WATER CONTENT OF SOIL DURING DRAINAGE OF CLAY COLUMN

It was not possible with the present methods to examine critically pressure potential conditions within the wetting zone. Data for this zone are included only to indicate when tensiometers were beginning to react. Apparently, from conditions at the base of the drainage zone, water moved into the wetting zone at a lower pressure potential in the loam than in the sand column after drainage had been in progress for 20 hours. In the sand column, the pressure potential at the base of the drainage zone remained at a value of about $-40g$ ergs/gm. while this zone was being extended downward during drainage. In the loam column, on the other hand, the value decreased from about $-20g$ to $-80g$ with increasing period of drainage. The decrease in pressure potential with depth near the base of the drainage zone in the clay column is apparently a result of the extremely slow movement of water within the drainage zone. The same condition was evident in a second clay column wetted to only 40 cm. to check this result.

Apart from this exception in the clay column, the gradient of pressure potential in the drainage zone was relatively uniform with depth in the later stages of drainage. Movement of water through this zone proceeded, in the assumed absence of osmotic effects, under the influence of gravity and against an opposing force due to the gradient in pressure potential. The sum of the pressure potential gradient (taken as $-0.6g$ dynes/gm. in the sand and loam columns) and the gravitational potential gradient (g dynes/gm.) is $0.4g$ dynes/gm. Consequently water flowed downward (in the direction of decreasing total potential) under a driving force of $0.4g$ dynes/gm. No particular value can be assigned to the driving force at field capacity for all soils, but these considerations indicate the relative contribution of pressure and gravitational forces in two of the cases examined.

The effect of depth of wetting on the gradient in pressure potential within the drainage zone was not examined. It seems likely that for equivalent periods of drainage the value of the gradient would be smaller numerically in part or whole of the drainage zone if much longer wetted columns were used. The difference in gradient at the two Winkie sand localities may be due to differences in extent of the drainage zone.

Pressure potential at field capacity

It is not possible to define with precision the stage of drainage at which a soil has reached field capacity. Nevertheless the term is a useful one, and it is worth while examining related pressure potential conditions. It can be seen from the preceding discussion that for any given period of drainage which may be considered appropriate to the attainment of field capacity in a particular uniform soil, the pressure potential will not be uniform at all depths within the drainage zone. Mean values have consequently been taken for the full drainage zone. They correspond to drainage periods of about 28, 45, and 120 hours respectively in the sands, the loam, and the clay. At this stage, pressure potential changed with time at a greatly decreased rate in the sands and loam but not in the clay. Difficulty in defining the stage at which a soil is at field capacity can be expected to be greatest in soils of high clay content. Moore (7) has made the generalized statement that although the order of permeability of soils may be sand > loam > clay for pressure potentials greater than $-100g$ ergs/gm., the order will be reversed for pressure potentials less than $-100g$ ergs/gm. In other words, a clay soil which has a low permeability when relatively saturated may become a better conducting medium than a sand or a loam under specified conditions of unsaturation. In these circumstances it will be more difficult to define a stage appropriate to field capacity in the clay than in the sand, since the decline in permeability will proceed more gradually in the clay. The results given in figures 1 and 2 are of interest in connection with Moore's statement. The pressure potential decreases more rapidly at first in the sand than in the loam and later, after the sand has reached field capacity, more rapidly in the loam than in the sand. Since water moving forces are similar at comparable stages of drainage in both columns, this reversal is probably associated with more rapid decrease in permeability of sand.

In the Winkie sand (field trials) the average value of pressure potential at field capacity is $-66g$ ergs/gm. for the depths and times of drainage given in

table 2. This compares closely with a value of $-70g$ ergs/gm. given earlier (5) for this soil type under somewhat different conditions of application, drainage period, and depth of measurement. In the sand and loam columns, the mean pressure potential at a stage which represented the laboratory equivalent of field capacity was $-55g$ and $-90g$ ergs/gm. respectively. These values are of a similar order to published values for pressure potential³ at field capacity. Rogers (9) found a range from $-55g$ to $-95g$, Richards and Weaver (8) suggested a value of about $-100g$, Colman (4) found a value of $-50g$ for a clay loam, and Smith and Browning (11) found a range from $-25g$ to $-125g$ in soils which had been fully wetted. Colman also determined the pressure potential indirectly on samples taken from the same soil and obtained a much lower value of $-160g$ ergs/gm., possibly because the water content at field capacity and the corresponding pressure potential were determined on soils of different structure.

The rate of drainage was extremely slow in the clay column. Pressure potential within the drainage zone decreased only slowly and a stage of drainage corresponding to field capacity had to be selected somewhat arbitrarily. At the end of the selected drainage period of 120 hours, the pressure potential had a mean value of $-35g$ ergs/gm. Boynton (2) working with dense subsoils of silty clay loam and silty clay, which lost little water during drainage, also obtained high values with a mean of about $-25g$ ergs/gm. for depths of 1, 2, and 3 feet after draining for 3 weeks. Lower values were presented by Boynton for soil at a depth of 4 feet corresponding in that case to 6 weeks of drainage. No regular trend with respect to depth can be detected in his results for the upper 3 feet.

Figures 2 and 3 show that water content decreases while pressure potential increases with depth within the drainage zone of the clay and loam columns at the conclusion of the drainage trials. This unexpected relation was noted also in a silt loam column by Colman and Bodman (3) who attributed it to experimental error. It is not evident in their sandy loam column or in the sands (column and field trials) of the present investigations. It is not possible to attribute this relation to lag in response of the tensiometers in the drainage zone, since many of the middle and lower tensiometers had practically as much time in which to respond as had those in the upper portion of the columns. Because of hysteresis, the relation between pressure potential and water content during drying of a soil depends on the initial degree of wetting, and lack of agreement may be due partly to the greater degree of wetting reached within the transmission zone than at lower levels. But this does not explain why a unique relationship does not exist within the depth equivalent to the original transmission zone. Possibly, structural changes in the clay and loam columns, resulting progressively from the passage of water, may have caused an increase in the pore space (per unit mass of soil) that was capable of remaining full of water at the final pressure potential. It appears, for example, that considerable expansion occurred at the top of the clay column since, at the end of the drainage period, the water content at depths of 5 and 10 cm. (53 and 48 per cent respectively) exceeded that calcu-

³ Most of the published values are given in terms of tension in centimeters of water. In such cases they have been multiplied by $-g$ for uniformity with the present treatment.

lated for pore space saturation. This had a value of 44 per cent by weight when calculated from the original apparent density (1.22 gm./cc.) and an assumed particle density of 2.65 gm./cc. A slight subsidence in the surface of the loam and a slight rise in the surface of the clay occurred after water had been added.

SUMMARY

The pressure potential of water was measured during entry into uniform soil in the field and into packed columns of sand, loam, and clay. During the application of water, the pressure potential at depths greater than 5 cm. did not vary with depth within the transmission zone of the sand and loam columns and of the field soil. There was a slight decrease with depth in the clay column. The pressure potential at this stage varied between $-4g$ and $-18g$ ergs/gm. in different soils. It was not consistently affected by different methods of applying the water (flood and spray) or by different rates of application of water as spray.

At the stage of drainage where field capacity (or its laboratory equivalent) had been attained, water moved downward within the drainage zone under a driving force which was less than g dynes/gm. in uniform soil. At this stage the pressure potential increased uniformly with depth in the drainage zone. The gradient in pressure potential represented in different soils a force between $-0.2g$ and $0.6g$ dynes/gm. opposing downward movement.

The mean value of pressure potential for all depths in the drainage zone at this stage (corresponding to field capacity) was $-66g$, $-55g$, $-90g$ ergs/gm. in the field soil and in the sand and loam columns respectively. The rate of drainage was extremely slow in the clay column, and a higher value of $-35g$ ergs/gm. was adopted in that case.

REFERENCES

- (1) BODMAN, G. B., AND COLMAN, E. A. 1944 Moisture and energy conditions during downward entry of water into soils. *Soil Sci. Soc. Amer. Proc.* (1943) 8: 116-122.
- (2) BOYNTON, D. 1939 Capillary tension as a measure of the pore space unoccupied by water in some dense orchard subsoils. *Soil. Sci.* 47: 347-354.
- (3) COLMAN, E. A., AND BODMAN, G. B. 1945 Moisture and energy conditions during downward entry of water into moist and layered soils. *Soil Sci. Soc. Amer. Proc.* (1944) 9: 3-11.
- (4) COLMAN, E. A. 1946 A laboratory study of lysimeter drainage under controlled soil moisture tension. *Soil Sci.* 62: 365-382.
- (5) MARSHALL, T. J. 1945 Tension of water in a sandy soil at field capacity. *Jour. Aust. Inst. Agr. Sci.* 11: 192-194.
- (6) MARSHALL, T. J. 1946 Ceramic instruments for use in the investigation of water in soils. *Aust. Council Sci. and Indus. Res. Jour.* 19: 166-171.
- (7) MOORE, R. E. 1939 Water conduction from shallow water tables. *Hilgardia* 12: 383-426.
- (8) RICHARDS, L. A., AND WEAVER, L. R. 1944 Moisture retention by some irrigated soils as related to soil moisture tension. *Jour. Agr. Res.* 69: 215-235.
- (9) ROGERS, W. S. 1939 Root studies: VIII. *Jour. Pomol. and Hort. Sci.* 17: 99-130.
- (10) ROWE, P. B. 1940 The construction, operation and use of the North Fork infiltrometer. U. S. Dept. Agr. Flood Control Coordinating Com. Misc. Pub. 1.
- (11) SMITH, R. M., AND BROWNING, D. R. 1948 Soil moisture tension and pore space relations for several soils in the range of the "field capacity." *Soil Sci. Soc. Amer. Proc.* (1947) 12: 17-21.

A NEW TECHNIC FOR DETERMINING WILTING PERCENTAGE OF SOIL

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The permanent wilting percentage of a soil is an important soil-moisture value and is useful as a basis for interpreting plant and soil-moisture relations. Briggs and Shantz (3) found that the percentage moisture remaining in a soil when the plants attain a permanent wilt is the same for all plants and can be computed by dividing the moisture equivalent by 1.84. They selected this factor after a study of many soil types and many species and varieties of wild and cultivated plants. Because of the interest in soil-plant-moisture relations, the conclusions of these workers have been subjected to critical study by students in this field. These later investigations showed general agreement with the conclusion of Briggs and Shantz that there is a common wilting percentage for all plants but not that the relation between the wilting percentage and moisture equivalent is constant for all soils. It is now rather generally conceded that the wilting percentage of a soil should be determined by growing plants in sealed containers of soil until permanent wilt is attained. The percentage moisture in the soil at this point is the wilting percentage.

The wilting point of any given soil is best described as the soil moisture percentage at which the suction pressure of the plant will just equal the back pull of the soil for moisture. This represents a moisture tension of approximately pF 4.2. It is a function of a limited layer of soil in close contact with the absorbing zone of the roots and not of the soil mass as a whole, as shown by Magistad and Breazeale (4).

As the plant draws water from the soil in immediate contact with the roots, more water moves toward the absorbing zone. In some soils this movement is so seriously restricted that when a large volume of soil is used for a determination of the wilting percentage the method may be subject to an error of considerable magnitude. Obviously this error can be reduced by using a relatively small volume of soil. The entire length of a root is not an absorbing zone.

Breazeale (1) and Breazeale and Crider (2) have demonstrated the ability of plants to build up the moisture content of a soil by absorbing water from one soil zone and exuding it into another zone if the latter is below the wilting percentage. A modification of this technic has been used to determine the wilting percentage of the soil.

EXPERIMENTAL

Tomato plants were grown in pots of soil until they were 1 to 2 months old. At this stage the lower stems were stripped of leaves so as to give a bare stem length of 10 cm. above the surface of the soil. Glass tubing, 3 cm. by 5 cm., was then slipped over the plant and a cork stopper fitted to the bottom of the tube

and sealed in place with a paraffin-beeswax mix to make a watertight seal. The soil was poured into the glass tube around the stem, and then the required amount of tap water was added to bring the soil to a desired moisture percentage. A cork fitting was made to the top of the glass tube to complete the watertight seal of the jacket. By this technic it is possible to grow a healthy plant in a large pot of soil which can be kept at optimum moisture content and produce another set of roots on the stem surrounded by soil in the glass jacket. The experimental setup is shown in figure 1.

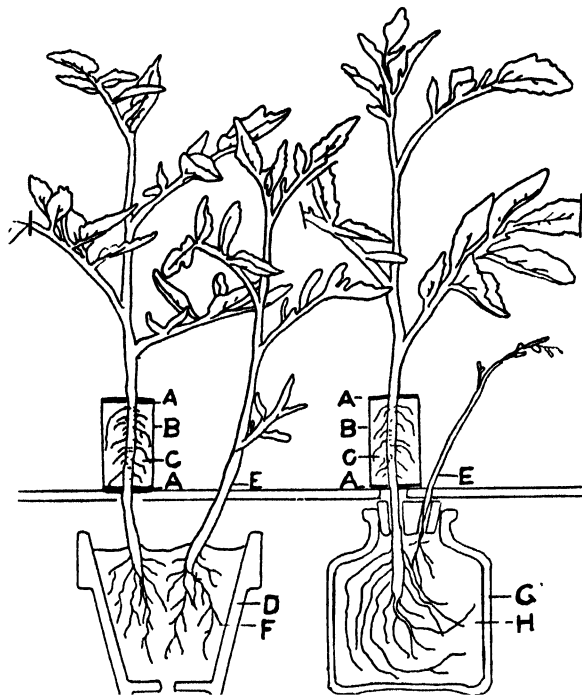


FIG. 1. METHOD OF DETERMINING THE WILTING PERCENTAGE

A, cork-beeswax seal; B, glass jacket; C, soil; D and G, containers; E, control plant F, soil; H, culture solution.

With this technic, many tests were conducted over several years. The data shown in figure 2 are those from a typical single experiment. A group of tomato plants was grown, three plants per pot of soil, and glass jackets were fitted to each plant as already described. Jacket 1 contained over-dry soil of 0 moisture content, number 2 was filled with soil of 6 per cent moisture content, and number 3 with a soil of 28 per cent moisture content. Tap water was used to adjust the soils to the desired moisture content. At the end of 2 weeks roots were visible on the stem enclosed in the glass jacket containing the soil at 28 per cent moisture. At the end of 3 weeks one plant was removed from each of the jackets which had been adjusted to different moisture contents. The soil was removed from the sealed jackets and moisture determined by drying in an oven at 105° C. The

removal of soil from another set of jackets was repeated at intervals for 10 weeks from the date the experiment was started. The moisture percentages obtained are given in figure 2. The moisture equivalent of this soil was 21.25 per cent and the calculated wilting percentage, $M.E./1.84$, was 11.5.

In a number of our experiments the jacketed tomato plants have been grown in culture solutions as well as in soil, as shown in figure 1. With this modification

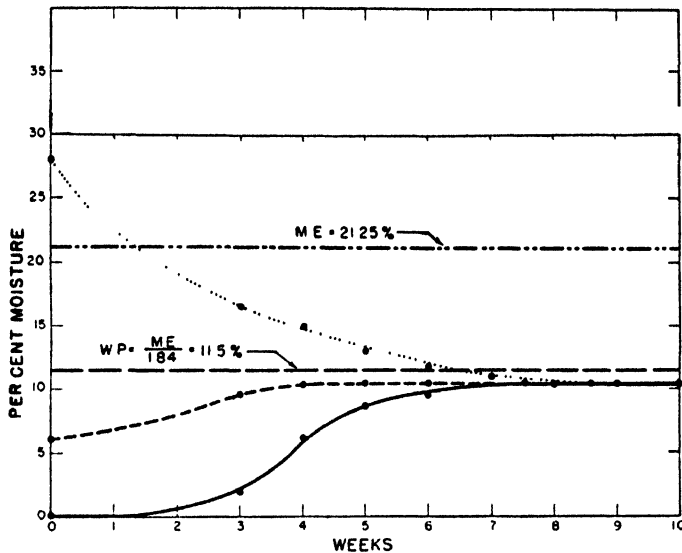


FIG. 2. APPROACH OF SOIL IN JACKETED TUBE TO WILTING PERCENTAGE

TABLE 1

Moisture loss in jacketed soils in which roots are already present on the stems

Original moisture percentage.....	10.5	16.5	35.0	60.0
Moisture percentage after 1 week....	10.5	11.5	18.2	22.3
Moisture percentage after 10 days....	10.5	10.4	10.5	10.5
Moisture percentage after 14 days.....	10.5	10.5	10.5	10.5

in technic the results obtained are in agreement with those obtained by growing the plants in a substrate of soil.

The application of this technic to the determination of the wilting percentage was demonstrated in another way. Three pots of soil were planted to four tomato plants each. When the plants were sufficiently large, the stems of each were jacketed and the jacketed soil was allowed to reach the wilting percentage. Additional time was allowed for the appearance of roots on all the jacketed stems. At this stage, one jacketed stem was left undisturbed in each of the three pots. The jackets on the other three plants were opened and 10 ml. of water was added to one, 5 ml. to another, and 1 ml. to the last. These moisture additions gave plants jacketed with soil at the wilting percentage, at 16.5 per cent water, at

35 per cent water, and at 60 per cent water. All the jackets were resealed. At 7, 10, and 14 days after the jackets had been resealed, the soils were removed from a set of plants and the moisture percentages of the jacketed soils determined. These data are given in table 1.

SUMMARY AND CONCLUSIONS

This experiment shows that the wilting percentage of a soil can be determined by the technic described. All the jacketed soils reached a constant moisture percentage in 7 weeks. At the end of this period a well-developed root system had appeared in all the jacketed soils. In the second part of the experiment, where the roots were already present on the jacketed stems, the time required for the soils to reach the wilting percentage was only 10 days.

At the wilting percentage, the soil moisture and the plant are in equilibrium. There is some question as to just how closely this can be attained throughout the soil mass by growing plants in a sealed pot of soil, as this method requires a relatively large volume of soil. For the jacketed tube method as little as 20 gm. of soil can be used.

The experiment shows that the tomato plants reduced the water in the wettest soil from 28 per cent to 10.5 per cent and also raised the moisture in the driest soil from 0.0 to 10.5 per cent. It also shows that when the moisture percentage is increased or reduced to the wilting percentage in the jacket, by this method, the moisture percentage in the jacketed soil remains constant for an indefinite period.

The plant is not dependent upon the soil in the jacket for its source of water. Therefore a moisture equilibrium between the soil and the plant can be attained with little or no moisture stress on the plant. It appears to be a simple example of how the plant follows the line of least resistance. The pull of the roots in the jacket is equal to that of the roots in the substrate. Since the amount of soil in the jacket is small compared to the amount in the substrate, the roots attain equilibrium first in the smaller volume of soil.

In heavy soils there is considerable resistance toward the movement of water from the soil mass at any great distance from the absorbing zone of the roots. This error is greatly reduced by the technic described in which a small volume of soil can be used.

REFERENCES

- (1) BREAZEALE, J. F. 1930 Maintenance of moisture equilibrium and nutrition of plants at and below the wilting percentage. *Ariz. Agr. Exp. Sta. Tech. Bul.* 29.
- (2) BREAZEALE, J. F., AND CRIDER, F. J. 1934 Plant association and survival, and build-up of moisture in semiarid soils. *Ariz. Agr. Exp. Sta. Tech. Bul.* 53.
- (3) BRIGGS, L. J., AND SHANTZ, H. L. 1912 The wilting coefficient of different plants and its indirect determination. *U. S. Dept. Agr. Bur. Plant Indus. Bul.* 230.
- (4) MAGISTAD, O. C., AND BREAZEALE, J. F. 1929 Plant and soil relationships at and below the wilting percentage. *Ariz. Agr. Exp. Sta. Tech. Bul.* 25.

EFFECT OF MAJOR ELEMENTS ON THE NIACIN, CAROTENE, AND INORGANIC CONTENT OF YOUNG OATS

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In recent years some interest has been stimulated by various articles (1, 2, 3, 5, 17) relating the health of animals and man to the fertility of soils. Although it is generally accepted that climatic conditions and genetic variations are the major factors affecting the vitamin content of plants, the question of the effect of inorganic nutrition is an important phase of the problem. Watson and Noggle (19) conducted a study of the riboflavin and ascorbic acid content of young oat plants when grown in various nutrient solutions each of which was completely deficient in one of the major elements. The minor elements have received considerable attention from Lyon *et al.* (12, 13), who studied the effects of trace element deficiencies and toxicities on turnips and tomatoes with reference to some of the B-vitamins. A reasonable amount of work has been carried out along these lines and some reviews (6, 7, 14) have been made; however, before any definite conclusions concerning this question can be made, an enormous amount of work of this type must be done.

In the initial phase of this problem one approach is the substitution of sand culture for soil as a growing medium for the plants. Although this technique has some advantages, there is no way at present of directly relating the results of sand culture work to the soil. Possibly relationships can be established through the correlation of the inorganic analysis and vitamin content of the plant. If this is true it should be emphasized that a sufficient number of plants must be grown under the same treatment and analyzed individually to establish the content of any one substance in the plant tissue within a fairly narrow range. Further, since it is the exception rather than the rule for a soil to be completely deficient in one or more of the major elements, any information derived from growing plants in totally deficient nutrient solutions would include visible plant-deficiency symptoms, indications of the possible roles of inorganic ions in the plant, but no quantitative relations between inorganic nutrition and vitamin content of the plants. The work described in the present paper is a record of the effect of decreased concentrations of the major nutrient elements on the composition of the plant tissue and the relationships among the amounts of the various inorganic ions and of niacin and carotene in the plant tissue.

EXPERIMENTAL PROCEDURE

Wintok oats No. CI 3424 obtained from the Oklahoma Agricultural Experiment Station was the plant used in this work. The seeds were germinated in

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flats containing pure quartz sand which had been previously leached with hydrochloric acid and washed with distilled water. The seeds were planted in flats on June 11, 1948 and then watered with distilled water. When 11 days old the seedlings were transplanted into pure quartz sand in 4-inch glazed soil jars and the different treatments were watered with their respective nutrient solutions.

The work was divided into two phases which were run concurrently.

The first phase was designed to determine the effect of individual plant variation and location in the greenhouse on the composition of the tissues. This experiment consisted of 157 pots, each containing five oat plants. These pots were randomized throughout the greenhouse and were all given the complete nutrient

TABLE 1
*Composition of the nutrient solutions**

TREATMENTS	Ca(NO ₃) ₂	KNO ₃	KH ₂ PO ₄	MgSO ₄	NaNO ₃	CaCl ₂	KCl	NaH ₂ PO ₄	Na ₂ SO ₄	MgCl ₂
Control	5.00	5.0	1.0	2.0	0.0	0.0	0.0	0.00	0.0	0.0
Low calcium	1.25	5.0	1.0	2.0	7.5	0.0	0.0	0.00	0.0	0.0
Medium calcium	2.50	5.0	1.0	2.0	5.0	0.0	0.0	0.00	0.0	0.0
Low potassium	5.00	1.5	0.0	2.0	3.5	0.0	0.0	1.00	0.0	0.0
Medium potassium	5.00	3.0	0.0	2.0	2.0	0.0	0.0	1.00	0.0	0.0
Low magnesium	5.00	5.0	1.0	0.5	0.0	0.0	0.0	0.00	1.5	0.0
Medium magnesium	5.00	5.0	1.0	1.0	0.0	0.0	0.0	0.00	1.0	0.0
Low sulfate	5.00	5.0	1.0	0.5	0.0	0.0	0.0	0.00	0.0	1.5
Medium sulfate	5.00	5.0	1.0	1.0	0.0	0.0	0.0	0.00	0.0	1.0
Low phosphate	5.00	5.0	0.0	2.0	0.0	0.0	1.0	0.25	0.0	0.0
Medium phosphate	5.00	5.0	0.0	2.0	0.0	0.0	1.0	0.50	0.0	0.0
Low nitrate	0.00	3.5	1.0	2.0	0.0	5.0	1.5	0.00	0.0	0.0
Medium nitrate	2.50	2.5	1.0	2.0	0.0	2.5	2.5	0.00	0.0	0.0

* Salt concentrations are reported in millimoles per liter.

solution. This phase furnished the control plants for the second phase and aided in interpreting the results.

The second phase consisted of growing the plants in decreased concentrations of calcium, magnesium, potassium, nitrate, sulfate, and phosphate. The treatments totaled 13, including the control plants, and the nutrient solutions employed are indicated in table 1. There were 10 pots to each treatment with five plants per pot. The concentrations of each of the major elements used were one fourth, one half, and full control. In this paper the plants receiving one fourth the control concentration of an ion will be referred to as "low," and those plants receiving half the control concentration will be referred to as "medium." The complete nutrient solution used was solution 1, method B, of Hoagland and Arnon (8). The following watering system was used: Approximately 100 ml. of nutrient solution was introduced into each pot every day. Once a week the pots were flushed with distilled water to prevent undue salt accumulation.

At harvest, the plants receiving reduced nitrogen treatments were the only

ones to appear chlorotic or stunted. Beginning August 3, the oats were harvested for the various analyses on successive days in the following order: inorganic of both phases, carotene analysis of both phases, niacin analysis of phase I, niacin analysis of phase II. The plants to be harvested were watered thoroughly with distilled water the preceding evening and harvesting was started at 3:00 a.m. to minimize transpirational effects on the fresh weights of the plants. The harvesting consisted of cutting the plant at the first node, cleaning the plant, and immediately determining the fresh weight of the tops.

METHODS OF ANALYSIS

Preparation for inorganic analysis consisted of air-drying the plants, oven-drying to a constant weight, and grinding them individually in a small Wiley Mill, using a 60-mesh sieve. Afterward the ground material was placed in an oven overnight at 105° C., then stored in desiccators to await analysis.

With the exception of the magnesium and sulfate determinations, the inorganic analyses were made on individual plants. Because of the limited amount of ground material for analysis, the magnesium and sulfate determinations were made on composite samples consisting of three individual plants. Nitrogen was determined by a semimicro Kjeldahl method run in duplicate. For the determination of calcium, potassium, phosphorus, and sodium, Walkley's wet-ash method described by Piper (16) was used; magnesium samples were prepared by the dry-ash method described by Wall (18). The individual determinations of calcium, magnesium, potassium, and sodium were made on a Beckman flame spectrophotometer. The determination of phosphorus was made by measuring the absorption of light by the blue solution formed when phosphomolybdic acid was reduced with sodium bisulfite and hydroquinone. The optical densities of these solutions were read in a Fisher electrophotometer at 650 M μ . Sulfate was determined by the magnesium nitrate ashing method described by Loomis and Shull (11).

The carotene determination used was the chromatographic method described in Methods of Vitamin Assay (4). Crude chlorophyll was determined colorimetrically with Guthrie's solution as a standard (11).

Plants were prepared for niacin analysis as described in Methods of Vitamin Assay (4).

The assay procedure used was the microbiological technique of Krehl, Strong, and Elvehjem described by Johnson (9) with slight modifications. These modifications are of general application to the technique of microbiological assays and will be described in a later paper.

RESULTS AND DISCUSSION

Results of the analyses of the oat plants are summarized in table 2. The higher percentages of calcium found in the plants receiving reduced amounts of potassium and the higher percentages of potassium in the plants receiving reduced amounts of calcium are perhaps noteworthy. Nightingale *et al.* (15), working with tomatoes, and Loehwing (10), working with oats, wheat, and corn, found

the concentrations of potassium were usually higher in plants receiving low amounts of calcium than in those receiving greater amounts. Watson and Noggle (19), however, reported that a deficiency of calcium resulted in the reduction of potassium content in oats, a tendency which appears to be opposite to that noted in the present study. The sulfur content of the oats receiving the low and medium calcium treatments was higher than that in the controls. The data of Nightingale *et al.* indicated a slightly opposite tendency, which the authors did not consider significant. These relationships merit further study.

TABLE 2
Composition of oats grown with different nutrient solutions

TREATMENT	CONTENT OF ELEMENTS, DRY WEIGHT BASIS								NIACIN CONTENT				CAROTENE AND CHLOROPHYLL CONTENT		
	Number of plants analyzed	Ca	Mg*	K	Na	S*	P	N	Number of plants analyzed	Niacin per gm fresh weight	σ	$\alpha \sigma$ at 1% level	Number of plants analyzed	Carotene† per gram fresh weight	Chlorophyll† per gram fresh weight
		per cent	per cent	per cent	per cent	per cent	per cent	per cent							
Control.....	155	1.41	.50	6.29	.00	.67	.39	3.96	157	9.21	1.68	0.35	15	28	1.4
Low Ca.....	10	0.37		7.01	.78	.79	.49	3.80	10	8.46	2.08	2.25	10	12	1.4
Medium Ca	8	0.93		6.79	.52	.76	.40	3.83	10	8.13	1.61	1.74	10	20	1.2
Low Mg...	9	1.25		5.60	.23	.59	.36	4.05	9	8.16	1.55	1.81	10	29	1.4
Medium Mg	10	1.43	.26	6.58	.25		.36	3.88	10	7.65	1.89	2.04	10	34	1.7
Low K...	10	2.14		3.52	.81		.49	3.72	9	8.68	1.91	2.24	10	16	1.2
Medium K.	10	1.82		4.69	.24	.55	.45	4.03	8	8.55	1.49	1.97	10	21	1.1
Low SO ₄ ...	9	1.55	.50	5.63	.00	.28	.40	3.62	10	8.29	1.51	1.63	10	22	1.3
Medium SO ₄	10	1.58		5.52	.00	.36	.33	3.84	10	8.99	1.25	1.35	10	21	1.3
Low PO ₄	10	1.50	.37	6.13	.00		.24	3.67	10	9.38	1.87	2.02	10	33	1.2
Medium PO ₄	10	1.07	.35	6.07	.00		.29	3.77	10	8.32	1.91	2.06	10	29	1.5
Low NO ₃	10	1.22	.46	6.16	.00		.33	2.89	9	5.16†	1.36	1.59	10	7	0.7
Medium NO ₃	10	1.60		5.63	.00	.42	.47	3.42	10	5.93†	1.40	1.51			

* Results of composite samples consisting of three individual plant samples.

† Based on three replicate composite samples from 15 plants in the controls and duplicate composite samples from 10 plants in all other treatments.

‡ Difference from controls significant at 1% level.

The arithmetic mean of the niacin content of the control plants was 9.21 γ per gram fresh weight. The standard deviation for 157 plants analyzed individually was 1.68. Of these plants 5.1 per cent exceeded two standard deviations from the mean and 27.4 per cent exceeded one deviation from this mean. None of the plants exceeded three standard deviations from the mean. The standard deviations of the niacin content of oats are listed in table 2. The consistency of the values of the standard deviations of all the treatments indicates the consistency of the experimental conditions and methods of analyses. No correlations could be established between the niacin content and the location of the plants in the greenhouse. Although this does not mean that the niacin content was completely independent of the position of the plants in the greenhouse, it

does indicate that any error due to this cause was so small that it was masked by the deviation of the individual plant variations. Though most of the treatments did not reduce the niacin content by amounts which are statistically significant, the results are worthy of some consideration. The plants receiving the low concentration of the calcium, magnesium, potassium, and phosphate ions contained a higher amount of niacin than the plants receiving the medium amounts of the ions, whereas the low sulfate and nitrate treatments contained less niacin than the medium sulfate and nitrate treatments. It appears that the effect of reduced concentrations of the elements studied on the niacin content of the oats increased in the following order: phosphorus, sulfur, potassium, calcium, magnesium, and nitrogen. This order of effect of these elements is similar to that found on riboflavin by Watson and Noggle (19).

Although every treatment except low phosphorus resulted in a lower niacin value than the controls, the difference was statistically significant only in the low and medium nitrogen treatments. If more plants are run with these treatments the range of the true mean value (mean $\pm \alpha\sigma$) probably will be established within narrower limits and the apparent anomaly of the magnesium treatments as well as the calcium treatments resolved.

The effects of reduced concentrations of nitrogen, calcium, and potassium on the carotene contents of the plants studied should be noted. The carotene contents of the oats treated with low nitrate, low calcium, and low potassium solutions were approximately 25 per cent, 50 per cent, and 50 per cent of that of the controls. When the calcium content of the tissue is plotted against carotene content a straight line results, which indicates a possible correlation between calcium and carotene. This is also true of potassium and carotene. It seems probable that such differences may be of considerable significance in determining the nutritive value of the forage from such plants. It should be remembered, however, that these values are results of only two analyses per treatment and of three analyses of the control plants.

Except for the low nitrogen treatment and probably the reduced potassium treatments, the effect on chlorophyll content does not appear to be significant.

SUMMARY

Oat plants were grown in sand culture with the major ions at three different concentrations in the nutrient solutions. When the plants were $7\frac{1}{2}$ weeks old they were harvested and analyzed for calcium, magnesium, potassium, sodium, sulfur, phosphorus, nitrogen, niacin, carotene, and crude chlorophyll.

Decreasing the concentration of ions in the nutrient solution resulted in a reduction in the concentration of the corresponding elements in the plant tissue. Reduction of the concentration of calcium in the nutrient solution resulted in an increase in the percentage of potassium and a slight increase in the percentage of sulfur in the plant tissues. Reduction in the concentration of potassium in the nutrient solution resulted in an increase in the percentage of calcium in the tissue.

With the exception of the low phosphorus plants, decreased concentration of each of the major elements in the nutrient solution showed a tendency to reduce

the niacin content of the oat tissues. The low and medium nitrogen treatments produced the only significant decrease in niacin from its concentration in the control plants at the level of 1 per cent. Reduction of the concentrations of nitrate, calcium, and potassium resulted in decreases in the amount of carotene produced (per gram fresh weight) as compared to the control plants. Only slight differences in the production of chlorophyll were found except in the low nitrogen treatment, where the chlorophyll content was approximately half that found in the control plants.

REFERENCES

- (1) ALBRECHT, W. A. 1943 Soil fertility and the human species. *Chem. and Engin. News* 21: 221-227.
- (2) ALBRECHT, W. A. 1948 Climate, soil and health. I. *Oral Surg. Oral Med., and Oral Path.* 1: 199-214.
- (3) ALBRECHT, W. A. 1948 National pattern of tooth troubles points to pattern of soil fertility. *Jour. Missouri State Dental Assoc.* 28: 195-201.
- (4) Association of Vitamin Chemists, Inc. 1947 Methods of Vitamin Assay. Interscience Publishers, Inc., New York.
- (5) GILBERT, F. A. 1948 Mineral Nutrition of Plants and Animals. University of Oklahoma Press, Norman, Oklahoma.
- (6) HAMNER, K. C., AND MAYNARD, L. A. 1942 Factors influencing the nutritive value of the tomato. U. S. Dept. Agr. Misc. Pub. 502.
- (7) HAMNER, K. C. 1945 Minor elements and vitamin content of plants. *Soil Sci.* 60: 165-171.
- (8) HOAGLAND, D. R., AND ARNON, D. I. 1938 The water-culture method for growing plants without soil. Calif. Agr. Exp. Sta. Cir. 347.
- (9) JOHNSON, B. C. 1948 Methods of Vitamin Determination. Burgess Publishing Co., Minneapolis, Minnesota.
- (10) LOEWING, W. F. 1928 Calcium, potassium, and iron balance in certain crop plants in relation to their metabolism. *Plant Physiol.* 3: 261-275.
- (11) LOOMIS, W. E., AND SHULL, C. A. 1937 Methods of Plant Physiology. McGraw-Hill Book Co., Inc., New York.
- (12) LYON, C. B., BEESON, K. C., AND ELLIS, G. H. 1943 Effects of micro-nutrient deficiencies on growth and vitamin content of the tomato. *Bot. Gaz.* 104: 495-514.
- (13) LYON, C. B., AND BEESON, K. C. 1948 Influence of toxic concentrations of micro-nutrient elements in the nutrient medium on vitamin content of turnips and tomatoes. *Bot. Gaz.* 109: 506-520.
- (14) MAYNARD, L. A., AND BEESON, K. C. 1944 Some causes of variation in the vitamin content of plants grown for food. *Nutrition Abs. and Revs.* 13: 155-164.
- (15) NIGHTINGALE, G. T., ADDOMS, R. M., ROBBINS, W. R., AND SCHERMERHORN, L. G. 1931 Effects of calcium deficiency on nitrate absorption and on metabolism in tomato. *Plant Physiol.* 6: 605-631.
- (16) PIPER, C. S. 1944 Soil and Plant Analysis. Interscience Publishers, Inc., New York.
- (17) ROUNTREE, L. G. 1941 The health of registrants and the President's plan of rehabilitation. *Science* 94: 552-553.
- (18) WALL, M. E. 1940 Micro determination of some constituents of plant ash. *Plant Physiol.* 15: 537-545.
- (19) WATSON, S. A., AND NOGGLE, G. R. 1947 Effect of mineral deficiencies upon the synthesis of riboflavin and ascorbic acid by the oat plant. *Plant Physiol.* 22: 223-243.

LIME-INDUCED CHLOROSIS: RELATION BETWEEN ACTIVE IRON AND CITRIC AND OXALIC ACIDS

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Chlorosis, a reduction in the chlorophyll content of leaves which is attributed to deficiencies of one or more of several micronutrient elements, is a major problem in the growing of crops on western soils. In Arizona the iron-, zinc-, and manganese-deficiency patterns occur in this order of abundance. Since they all occur on crops growing on calcareous soils, all three are classified as "lime-induced" in this state. Studies on orchard and field crops (4, 5) have shown no positive evidence of a deficient uptake, except possibly for manganese uptake in citrus. Manganese is consistently lower in chlorotic than in green citrus leaves. This is true for both iron- and zinc-deficiency patterns. No relation has been found between total iron or zinc and chlorosis.

The most consistent relation between green and chlorotic leaves is one obtained by determining the solubility of iron in normal HCl as proposed by Oserkowsky (6). With this method, chlorotic leaves, exhibiting both the iron- and zinc-deficiency patterns, show less active iron than do green leaves. Also the application of acidifying materials, such as sulfur, sulfur-manure mixture, and iron sulfate, to the soil increases the percentage of active iron in the leaves more often than it does the total iron uptake (4, 5).

A new approach to the chlorosis problem is that of Iljin (2, 3) and Schander (9, 10, 11), who studied the organic acids, particularly citric acid, in green and chlorotic leaves. They found a consistently higher citric acid content in chlorotic than in green leaves of deciduous fruits, lupines, and some other plants. Their research suggests that increase in the citric acid content of leaves proceeds approximately parallel to that of calcium and magnesium. Ordinarily the citric acid lags. If it gains ascendancy, chlorosis develops.

This paper presents the results of certain studies on chlorosis in Arizona in which citric and oxalic acid determinations were made on green and chlorotic leaves from orchard and field crops by the methods of Pucher *et al.* (7, 8).

STUDIES ON FIELD CROPS

The field crops included in this study were Sudan grass, sorghum (hegari), soybeans, peanuts, and cotton. These crops, with the exception of cotton, were severely chlorotic at the time samples were taken. As the fields were spotted with both green and chlorotic plants, samples of each were available. Leaves of the cotton, which was growing in the same soil with the other crops, bore many brown necrotic spots. The samples were analyzed for citric acid, oxalic acid, and percentage of active iron (active Fe/total Fe). The analyses are given in table 1.

Hegari leaf samples 941 and 942 are from young plants about 8 inches high,

and 981, 984, 1149, and 1150 are leaves from large plants after the grain heads had formed. Plants from which samples 981 and 1149 were taken had been side-dressed with a sulfur-manure mixture containing 100 pounds iron sulfate, 100 pounds manganese sulfate, and 50 pounds zinc sulfate per ton. These plants were severely chlorotic when side-dressed but were a normal green when the samples were taken. Samples 984 and 1150 are from chlorotic plants, not side-dressed, growing adjacent to samples 981 and 1149.

TABLE 1

Citric acid, oxalic acid, and active iron in green and chlorotic leaves of certain field crops
Dry-matter basis

SAMPLE NUMBER	CROP	LEAF SAMPLE	CITRIC ACID	OXALIC ACID	ACTIVE Fe* TOTAL Fe
			<i>mgm./gm.</i>	<i>mgm./gm.</i>	
936	Sudan	Green	3.8	5.6	96
940	Sudan	Chlorotic	6.5	9.8	29
946	Soybeans	Green	3.2	6.3	43
947	Soybeans	Chlorotic	24.2	4.4	29
1045	Peanuts	Green	8.1		57
1046	Peanuts	Chlorotic	17.7		27
941	Hegari	Green	4.7	1.3	42
942	Hegari	Chlorotic	4.2	1.3	21
981†	Hegari	Green	4.5	3.5	36
984	Hegari	Chlorotic	3.6	5.5	22
1149†	Hegari	Green	2.0	3.8	
1150	Hegari	Chlorotic	2.5	3.0	
949	Cotton	Green	41.7	5.2	
950	Cotton	Necrotic	58.4	2.2	

* Values in column obtained by dividing active Fe percentage by total Fe percentage.

† These plants were side-dressed with sulfur-manure mixture.

For the soybeans, peanuts, and cotton, citric acid is significantly higher in the chlorotic leaves. For all crops the percentage active iron is significantly lower in the chlorotic leaves. Oxalic acid is low in all these leaf samples and shows no significant relation to leaf condition. Both low percentage active iron and high citric acid are characteristic of the chlorotic leaves of the dicotyledons, whereas citric acid is low in the two monocotyledons and there is no significant relation to leaf condition. There is, however, a lower percentage active iron in the chlorotic monocotyledons, and it is further significant that the percentage active iron in leaves was increased by side-dressing with the acidified material that cured the chlorosis. Sudan grass and hegari are in the high-silica group of plants.

and added in salts. The pH values were obtained at the end of the experiments, by means of the glass electrode.

The pot experiment was conducted outdoors. Favorable conditions of soil moisture were maintained by rainfall and supplemental irrigation; provision was

TABLE 1
*Treatments applied to soils and resulting nutrient and pH levels**

TREATMENTS	OTTAWA FINE SANDY LOAM			MARDIN SILT LOAM		
	Exchange- able Ca	Exchange- able Mg	pH	Exchange- able Ca	Exchange- able Mg	pH
	me./100 gm.	me./100 gm.		me./100 gm.	me./100 gm.	
1. Check	5.6	1.3	5.00	4.0	1.2	5.15
2. MgHPO_4 †	5.6	1.6	5.10	4.0	1.8	5.25
3. $\text{Ca}(\text{H}_2\text{PO}_4)_2$ †	5.7	1.3	5.04	4.2	1.2	5.10
4. MgSO_4	5.6	4.3	4.75	4.0	4.2	4.90
5. CaSO_4	8.6	1.3	4.60	7.0	1.2	4.72
6. $\text{MgSO}_4 + \text{P}$ †	5.7	4.3	4.55	4.2	4.2	4.90
7. $\text{CaSO}_4 + \text{P}$	8.7	1.3	4.50	7.2	1.2	4.90
8. MgCO_3	5.6	4.3	5.55	4.0	4.2	5.75
9. CaCO_3	8.6	1.3	5.52	7.0	1.2	5.40
10. Na_2CO_3	5.6	1.3	6.60	4.0	1.2	6.20
11. $\text{MgCO}_3 + \text{P}$	5.7	4.3	5.34	4.2	4.2	5.30
12. $\text{CaCO}_3 + \text{P}$	8.7	1.3	5.50	7.2	1.2	5.60
13. $\text{Na}_2\text{CO}_3 + \text{P}$	5.7	1.3	6.55	4.2	1.2	6.70
14. MgSiO_3	5.6	4.3	5.65	4.0	4.2	5.15
15. CaSiO_3	8.6	1.3	5.25	7.0	1.2	5.50
16. Na_2SiO_3	5.6	1.3	6.50	4.0	1.2	5.80
17. Olivine	5.6	7.3	5.05	4.0	4.2	5.15
18. Serpentine	5.6	7.3	5.40	4.0	4.2	5.20
19. $\text{MgSiO}_3 + \text{P}$	5.7	4.3	5.55	4.2	4.2	5.30
20. $\text{CaSiO}_3 + \text{P}$	8.7	1.3	5.30	7.2	1.2	5.35
21. $\text{Na}_2\text{SiO}_3 + \text{P}$	5.7	1.3	6.45	4.2	1.2	5.80
22. Olivine + P	5.7	7.3	5.25	4.2	4.2	5.25
23. Serpentine + P	5.7	7.3	5.20	4.2	4.2	5.00

* Calculations of exchangeable bases based on plow layer (2 million pounds) of soil and on assumption of complete solubility of added materials. On both soils (basis 2 million pounds) the added Mg, Ca, and Na sulfates, carbonates, and silicates were equivalent to 3 me./100 gm. Values for pH at end of experiment.

† Equivalent to 150 pounds P_2O_5 /2 million pounds soil on Ottawa, 300 pounds P_2O_5 /A on Mardin. By modified Truog test (13) there were 60 and 3 pounds of available P_2O_5 per 2 million pounds of Ottawa and Mardin soils, respectively.

‡ As $\text{Ca}(\text{H}_2\text{PO}_4)_2$, at same rate as in treatment 3.

made for retaining leachings and returning them to the soil to avoid loss of nutrients. The soybeans were seeded on June 15, 1947. The aerial portions of the plants were harvested 60 days later, when pod development had just begun. Each pot of soil supported four plants.

The sudan grass on the field plots was seeded in drills on June 23, 1947, at the rate of 40 pounds per acre. An interplanting of ladino clover was made at the same time. The plots received natural rainfall, which amounted to approximately 0.72 inch to the end of June, 4.91 inches in July, and 5.74 inches to harvest time in August. Small samples of sudan grass for P determination were taken from all plots 4 weeks after seeding; the plots were harvested 8 weeks after planting, when head development had just begun. An area of 3.5 by 3.5 feet was harvested from the center of each 6 by 6-foot plot. Small samples of ladino clover plants were taken for P determination 4 weeks after the final harvest of sudan grass.

Sand-solution-culture experiment

Sudan grass was grown, in a greenhouse, in 2-gallon pots of quartz sand to which nutrient solutions of the composition given in table 4 were applied. Except for variations in P and Mg, all pots received the same nutrient concentrations. Four levels of P and three levels of Mg were applied in factorial combination. Each of the 12 treatments was replicated three times. Four sudan grass plants were grown in each pot. When the plants were 5 weeks old (planted September 28, 1947) the aerial portions were harvested; no heads had yet appeared.

Analytical procedures

All plant material was dried at 65° C., weighed (except sudan grass at 4 weeks and ladino clover), and ground in a Wiley mill. The soybeans and sudan grass were analyzed, by the methods described by Kelley, Hunter, and Sterges (8), for P, Mg, Ca, and K. Ladino clover was analyzed only for P. Nitrogen was determined by the Kjeldahl procedure (A.O.A.C.). The data obtained were reduced by the analysis of variance method; certain pairs of data were compared by Student's paired data method (15).

RESULTS

Experiments on soils

Table 2 shows the yield and composition of the soybeans grown on Ottawa fine sandy loam in pots.

In comparison with the check treatment the phosphates of Mg and Ca produced similar significant increases in yield, whereas significant decreases in yield resulted from application of the sulfates of Mg and Ca and the salts of Na. The other salts added by themselves did not affect the yield. Application of P along with any salt produced a higher yield than when the salt was applied alone. There were no significant differences between the yields produced by Mg and Ca carbonates and silicates, the latter including olivine and serpentine.

The concentration of P in the soybeans was affected little by treatment of the soil. The average for seven Mg treatments was 0.194 per cent; for seven Ca treatments, 0.191 per cent. The $MgSO_4$ treatment significantly increased the P content when applied alone and decreased it when applied with added P. A significant decrease resulted from the application of Na silicate. With these exceptions the treatments produced no significant differences in P content.

In comparison with the check treatment, all Mg treatments significantly increased the Mg content of the soybeans, which was practically doubled by the sulfate and increased to a smaller extent by the carbonate and silicate.

The data of the field plot test with sudan grass and ladino clover are set forth in table 3. Some weeds grew on the plots. To avoid the complicating factor of

TABLE 2
Mean yield and composition of soybeans on Ottawa fine sandy loam

TREATMENT*	CROP YIELD/ FOT	COMPOSITION OF CROP				
		P	Mg	Ca	K	N
	gm.	per cent	per cent	per cent	per cent	per cent
1	21.1	0.20	0.44	1.13	1.85	1.37
2	27.0	0.18	0.47	1.19	1.46	1.05
3	26.7	0.19	0.47	1.25	1.42	1.06
4	10.8	0.23	0.87	0.99	2.19	2.67
5	18.5	0.18	0.53	1.40	1.80	1.61
6	19.0	0.16	0.85	0.94	1.66	1.70
7	26.2	0.18	0.49	1.36	1.53	1.04
8	22.3	0.19	0.62	0.98	1.84	1.38
9	23.6	0.19	0.45	1.24	1.71	1.27
10	7.8	0.19	0.52	1.13	1.93	3.25
11	26.8	0.21	0.63	1.01	1.48	1.24
12	25.4	0.21	0.47	1.26	1.52	1.25
13	15.4	0.19	0.54	0.94	2.03	2.08
14	23.3	0.19	0.56	0.97	1.69	1.28
15	22.4	0.19	0.47	1.21	1.64	1.16
16	4.9	0.16	0.47	0.79	1.98	2.88
19	27.2	0.20	0.54	1.00	1.44	1.02
20	25.4	0.20	0.47	1.21	1.60	1.00
21	10.3	0.15	0.44	0.86	1.94	2.38
17	22.0	0.19	0.48	1.07	1.69	1.19
18	20.9	0.19	0.51	1.12	1.87	1.40
22	25.5	0.20	0.50	1.14	1.53	1.05
23	27.1	0.20	0.48	1.22	1.51	1.06
L.S.D. at P = 0.05	2.32	0.023	0.072	0.162	0.250	0.140
L.S.D. at P = 0.01	3.08	0.030	0.095	0.214	0.330	0.180

* See table 1.

mixed species, the sudan grass was separated by hand from other species at harvest time. The weights given are for sudan grass alone and, though they do not represent the total yield of the plots, they are thought to be, in a general way, representative of the differences produced by soil treatment.

The P content of the sudan grass was determined at maturities of 4 weeks and

8 weeks. At 4 weeks the sudan grass from the Mg-treated plots was significantly higher in P content than that from the Ca-treated plots; practically, the increase

TABLE 3

Mean yield and composition of sudan grass and ladino clover on Mardin silt loam

TREATMENT*	CROP YIELD/ PLOT†	COMPOSITION OF SUDAN GRASS						P CONTENT OF LADINO CLOVER
		P		Mg	Ca	K	N	
		4 wks	8 wks					
	gm.	per cent	per cent	per cent	per cent	per cent	per cent	per cent
1	72	0.24	0.33	0.24	0.49	1.98	1.19	0.32
2	160	0.27	0.30	0.29	0.40	1.54	0.82	0.38
3	135	0.29	0.30	0.22	0.44	1.35	0.79	0.37
4	155	0.28	0.32	0.52	0.31	1.73	1.22	0.28
5	82	0.26	0.36	0.22	0.51	1.61	1.16	0.30
6	219	0.32	0.28	0.40	0.24	1.29	1.01	0.31
7	258	0.26	0.25	0.16	0.47	1.43	0.71	0.37
8	108	0.31	0.30	0.49	0.43	1.57	1.23	0.32
9	74	0.25	0.34	0.25	0.54	1.90	1.07	0.34
10	86	0.30	0.26	0.23	0.36	1.57	1.58	
11	142	0.24	0.33	0.50	0.42	1.38	1.04	0.32
12	141	0.23	0.30	0.20	0.54	1.49	0.84	0.40
13	110	0.30	0.28	0.22	0.35	1.66	1.45	
14	77	0.28	0.35	0.35	0.42	1.68	1.06	0.30
15	99	0.26	0.32	0.23	0.50	1.74	1.06	0.34
16	163	0.29	0.31	0.25	0.38	1.95	1.17	
19	160	0.29	0.27	0.25	0.36	1.17	0.77	0.39
20	184	0.25	0.30	0.22	0.50	1.45	0.80	0.40
21	266	0.29	0.26	0.16	0.31	1.31	0.85	
17	72	0.26	0.32	0.26	0.48	2.04	1.15	0.30
18	83	0.26	0.32	0.29	0.40	1.96	1.14	0.29
22	178	0.27	0.30	0.22	0.44	1.38	0.88	0.38
23	162	0.25	0.30	0.26	0.49	1.37	0.85	0.39
L.S.D. at P = 0.05	70	0.036	0.040	0.060	0.08	0.33	0.20	0.042
L.S.D. at P = 0.01	93	0.047	0.050	0.080	0.11	0.44	0.27	0.057

* See table 1.

† 12.25 square feet harvested.

was of little importance. The mean value for the percentage of P in plants from all Mg-treated plots was 0.286; for all Ca-treated plots, 0.259.

The final harvest of sudan grass was made when the plants were 8 weeks old and heading had just begun. Analysis showed that in comparison with the check treatment none of the Mg, Ca, or Na salts had significantly increased the percent-

age of P in the plants. There was no difference in the mean values for the concentrations of P in the sudan grass from the Mg- and Ca-treated plots (seven treatments in each case, excluding olivine and serpentine but including phosphate), the value in each case being 0.31 per cent. This was true although the more soluble Mg salts—sulfate and carbonate—doubled the percentage of Mg in the plants in comparison with those grown on Ca-treated plots. The Na treatments, except for Na silicate applied alone, significantly decreased the P percentage.

Samples of ladino clover were taken for P determination 4 weeks after the harvest of the sudan grass. Because of the puddled condition of the soil surface that resulted from treatment with Na salts, no clover was established on the

TABLE 4
Mean yield and composition of sudan grass in sand-solution cultures

NUTRIENT SOLUTION	NUTRIENT CONCENTRATION*		CROP YIELD/POT	COMPOSITION OF CROP		NUTRIENT ABSORPTION BY CROP	
	P	Mg		P	Mg	P	Mg
	ppm.	ppm.	gm.	per cent	per cent	mmol.	mc.
1	1	5	0.16	0.13	0.20	0.0067	0.0263
2	1	25	0.21	0.14	0.38	0.0095	0.0658
3	1	100	0.20	0.15	0.47	0.0096	0.0772
4	3	5	1.57	0.45	0.10	0.226	0.129
5	3	25	1.88	0.33	0.23	0.201	0.355
6	3	100	2.37	0.32	0.34	0.245	0.656
7	9	5	15.03	0.43	0.19	2.09	2.35
8	9	25	20.00	0.41	0.36	2.65	5.92
9	9	100	14.72	0.38	0.47	1.80	5.69
10	27	5	27.45	0.70	0.22	6.20	4.97
11	27	25	34.92	0.72	0.56	8.12	16.08
12	27	100	29.42	0.72	0.66	6.84	15.95

* In addition to P and Mg, other elements were supplied uniformly, as follows: K, 195; N, 140; Ca, 160; S, 30; Fe, 1.5; Mn, 1; B, 0.5; Zn, 0.4; Cu, 0.1; and Mo, 0.1 ppm. The pH of the solutions was 5.4 ± 0.2 .

plots treated with Na and hence no samples could be obtained from these plots. There was no significant difference in the concentrations of P in the plants from the Mg- and Ca-treated plots. The mean value for seven Mg treatments was 0.33 per cent; for the corresponding Ca treatments, 0.36 per cent.

Sand-Solution-culture experiment

Both the dry weight yield and the concentration of P were markedly increased by increased supply of P in the sand-solution-culture experiment (except that the differences in P content of plants grown with 3 and 9 ppm. P were not significant) but were not significantly affected by the level of Mg (table 4). At all levels of P, however, the increase of Mg from 5 to 25 to 100 ppm. in the nutrient

solution resulted in highly significant increases in the percentages of Mg in the plants. There was a consistent increase in the Mg content with increasing supply of P from 3 to 9 to 27 ppm. Plants grown with 1 ppm. P were abnormal and suffered from P deficiency. Symptoms of P deficiency were also observed in some of the plants supplied with 3 ppm. P. Characteristic Mg-deficiency symptoms appeared in the plants supplied with only 5 ppm. Mg in combination with 27 ppm. P; at lower levels of P these did not appear.

GENERAL DISCUSSION

A comparison by the paired data method (15) of the percentages of P in the soybeans, sudan grass, and ladino clover from soils treated with equivalent quantities of similar salts of Mg and Ca showed that there were no statistically significant differences in the effects of these two elements on P uptake, except in sudan grass harvested at 4 weeks of age. The application of Na_2SiO_3 decreased the concentration of P in soybeans on the Ottawa soil and in sudan grass (8 weeks) on Mardin soil, in comparison with Mg and Ca salts. The Na salts, because of greater hydrolysis, produced reactions higher than the corresponding Mg and Ca salts, and brought about considerable dispersion of soil aggregates and solution of humic materials, resulting in unfavorable physical characteristics of the soils and decreased yields of the plants. The effects of the Na salts were evidenced by dark-colored percolates from the Ottawa soil and by dark color and puddled surface of the Mardin soil. The pH values given in table 1 were obtained at the end of the experiments and represent the reaction of the whole mass of the potted Ottawa fine sandy loam and of the upper 6 inches of the field plots of Mardin silt loam. Before treatment the Ottawa and Mardin soils contained, respectively, totals of 8.9 and 5.8 me. of Mg, Ca, and K per 100 gm. The applied Na was equivalent to 3 me. per 100 gm. in each case (basis 2 million pounds soil per acre for Mardin). Since puddling of soil and solution of humic materials do not normally occur at the pH values given in table 1, it is evident that the pH of the Na-treated soils was much higher early in the experiments than at the end. Plants on soils treated with either Na salts or MgSO_4 were darker green than those on soils of any other treatment; and were much higher in N.

The increased P content associated with Mg in sudan grass 4 weeks of age may be of some significance. Possibly an effect of Mg on P absorption, observed in plants 4 weeks old, may be obscured when the plants are 8 weeks old. The fact that the rate of nutrient absorption varies with the stage of development may explain the different results obtained at the two stages of maturity. Thomas (16) observed in his studies of foliar diagnosis that the concentration of P in plant leaves reached a maximum, after which it decreased regularly with increasing age of the leaf. The differences observed between the P content of the Mg- and Ca-treated sudan grass plants at 4 weeks, although consistent, were not great enough to permit definite conclusions. Effects at any stage of growth are of fundamental interest, but only those effects that persist until the normal harvest time for the plant are of practical importance. In the sand-solution-culture experiment where sudan grass plants were harvested when 5 weeks old

—1 week older at harvest time than was the sudan grass grown on the Mardin soil—variations in Mg level had no effect in increasing P absorption.

The soil treatments of these experiments theoretically resulted in three ranges of Ca-Mg ratios in the pots of soil or in plow depth of the field plots. The application of Mg salts produced Ca-Mg ratios between approximately 1:1 and 1.5:1; the check soils and those that received Na salts had Ca-Mg ratios in the range 3:1 to 4:1; and in the soils treated with Ca the range was between 6:1 and 6.5:1. The failure of Mg to promote increased uptake of P from these soils is in agreement with the results obtained in another investigation (7) in which alfalfa was grown on a series of soils having a wide range (1:4 to 32:1) of Ca-Mg ratios. Only small and unimportant increases in the P content of alfalfa resulted from increases in Mg within the range in which Ca exceeded Mg on the basis of chemical equivalency; significant increases in the concentration of P occurred only when Mg was increased to an amount equivalent to, or greater than, the Ca in the soil.

The data of these investigations and the literature cited show that increased supply of Mg does not under all circumstances result in increased uptake of P by plants. Several factors may tend to complicate or obscure any relationship that may exist between the Mg supply and the utilization of P.

If a soil is deficient in Mg, plants grown on that soil may be deficient in chlorophyll and hence have reduced capacity for synthesis of the carbohydrates required for production of a normal root system. In such a case the application of Mg may have a secondary effect on the absorption of P by the plant through its influence on the general vigor. In instances of deficient P supply no amount of Mg could be expected to cause a substantial increase in P uptake. The fact that in these tests plants from all treatments contained normal concentrations of Mg and P (2) indicates that deficiency of neither of these elements was a factor. The relative base status and the pH of the soil may also have effects. Little information is available on the total contents of available bases and P present in the soils employed in studies of the Mg-P relationship that have been reported in the literature. Such information should do much to clarify the reasons for the conflicting results that have been reported.

McGeorge (11) pointed out the importance of the indicator crop in drawing conclusions regarding the interrelationships between Mg and P. The importance of this factor cannot be overemphasized. Plants differ markedly in their abilities to obtain their supplies of P from the soil itself. Some plants grow normally under conditions that produce P-deficiency symptoms in others. Plants also show great variation in their reactions to limited Mg supply. It is probable, as Truog *et al.* (17) believed, that analysis of seeds of plants furnishes a more reliable test of the theory that Mg acts as a carrier of P than does analysis of vegetative tissue.

SUMMARY AND CONCLUSIONS

Effects of variations in Mg, Ca, and Na supplies upon P utilization by plants were studied and compared in three experiments. Soybeans and sudan grass with an interplanting of ladino clover were grown in pots and field plots of soil, re-

spectively, to which similar salts of Mg, Ca, and Na were supplied in equivalent amounts in combination with two levels of P. Sudan grass was grown in sand-solution cultures to which Mg was supplied at three levels in factorial combination with four levels of P and constant levels of other nutrients.

In comparison with Ca and Na, the application of Mg to soils markedly increased the percentage of Mg in soybeans and sudan grass; failed to increase significantly the percentage of P in soybean plants harvested as pod formation began, in sudan grass harvested 8 weeks after seeding, or in ladino clover harvested from the same plots 4 weeks after the sudan grass; and slightly but significantly increased the percentage of P in sudan grass harvested at 4 weeks of age. Variation in Mg level, in combination with constant levels of P, had no significant effects upon the P content of sudan grass grown in sand-solution culture and harvested at 5 weeks of age.

REFERENCES

- (1) BARTHOLOMEW, R. P. 1933 The availability of phosphatic fertilizers. *Ark. Agr. Exp. Sta. Bul.* 289.
- (2) BEESON, K. C. 1941 The mineral composition of crops with particular reference to the soils on which they were grown. U.S. Dept. Agr. Misc. Pub. 369.
- (3) BEESON, K. C., LYON, C. B., AND BARRANTINE, M. W. 1944 Ionic absorption by tomato plants as correlated with variations in the composition of the nutrient medium. *Plant Physiol.* 19: 258-277.
- (4) COOPER, H. P., PADEN, W. R., AND GARMAN, W. H. 1947 Some factors influencing the availability of magnesium in soil and the magnesium content of certain crop plants. *Soil Sci.* 63: 27-41.
- (5) FUDGE, B. R. 1941 The mineral composition of citrus juice as influenced by soil treatment. *Proc. Fla. State Hort. Soc.* 54: 4-12.
- (6) GERICKE, S., AND POLHEIM, M. P. von 1939 Versuche über die Wirkung von Ca and Mg-Verbindungen auf Boden und Pflanze. *Bodenk. u. Pflanzenernähr.* 13: 232-242.
- (7) HUNTER, A. S. 1949 Yield and composition of alfalfa as affected by variations in the Ca/Mg ratio in the soil. *Soil Sci.* 67: 53-62.
- (8) KELLEY, O. J., HUNTER, A. S., AND STERGES, A. J. 1946 Determination of nitrogen, phosphorus, potassium, calcium, and magnesium in plant tissue. *Indus. and Engin. Chem., Analyt. Ed.* 18: 319-322.
- (9) KELLOGG, C. E. 1931 Magnesium—a possible key to the phosphorus problem in semiarid soils. *Jour. Amer. Soc. Agron.* 23: 494-495.
- (10) LOEW, O. 1903 The physiological role of mineral nutrients in plants. U. S. Dept. Agr. Bur. Plant Indus. Bul. 45.
- (11) McGEORGE, W. T. 1939 Availability of phosphates in Arizona soils. *Ariz. Agr. Exp. Sta. Bul.* 82.
- (12) MILLER, E. C. 1931 *Plant Physiology*. McGraw-Hill, New York.
- (13) PEECH, M., et al. 1947 Methods of soil analysis for soil-fertility investigations. U. S. Dept. Agr. Cir. 757.
- (14) PIERRE, W. H. 1938 Phosphorus deficiency and soil fertility. *U. S. Dept. Agr. Yearbook* 1938: 377-396.
- (15) SNEDECOR, G. 1940. *Statistical Methods*. Iowa State College Press, Ames.
- (16) THOMAS, W. 1937 Foliar diagnosis—principles and practice. *Plant Physiol.* 12: 571-600.
- (17) TRUOG, E., et al. 1947 Magnesium-phosphorus relationships in plant nutrition. *Soil Sci.* 63: 19-26.
- (18) WILLIS, L. G., PILAND, J. R., AND GAY, R. L. 1934 The influence of magnesium deficiency on phosphate absorption by soybean plants. *Jour. Amer. Soc. Agron.* 26: 419-422.
- (19) ZIMMERMAN, M. 1947 Magnesium in plants. *Soil Sci.* 63: 1-12.

BOOKS

Der Boden, Second edition. By ARTUR JACOB. Akademie-Verlag, Berlin, 1949. Pp. 241. Price, paper-bound, 6.50 DM; hard covers, 10 DM.

This is a small textbook on soils. It presents an over-all view of the soil and then deals successively with its composition, profile, texture, structure, constitution, colloids, humus, as a carrier of plant nutrients, soil water, energy control, microbial content, soil-plant relationships, soil divisions, principal soil types, mapping, geography of European soils, soil research, working the soil, crop relationships, water control, and use of fertilizers. A list of 83 references is appended. This would be a very useful book for graduate students who are endeavoring to improve their reading knowledge of German.

A Booklet for the Educated Farmer. By PH. A. ANASTASSIADES. Anthipou 4, Pagrati, Athens, Greece (Obtainable from the author), 1949. Pp. 147.

For those who read Greek, this neatly printed little book will be of considerable interest. It deals with soils and fertilizers; the growing of crops, with special reference to wheat, vegetables, tree fruits, and grapes; control of plant diseases; production of livestock, including feeding and disease control; and principles of agricultural economy. It contains a series of tables with useful technical information on irrigation, agricultural buildings, and the use of concrete. The final chapter gives factors to English and American systems of weights and measures and tables that are helpful in agricultural calculations. Appended is a list of the references that were consulted in the preparation of the book.

Colloid Chemistry. Second edition. By HARRY BOYER WEISER. John Wiley and Sons, Inc., New York, 1949. Pp. 444, figs. 117. Price \$5.50.

The author indicates that his purpose is to acquaint students with the foundations of and classical experiments in colloidal chemistry, to have them understand the theories underlying colloidal behavior, and to have them appreciate the widely diversified applications of the science. The first chapter deals with the colloidal state, the next eight chapters with adsorption, the next ten chapters with sols; and there are two chapters each on gels, emulsions, and foams; aerosols and solid sols; and applications, the last with special reference to contact catalysis and dyeing. To each chapter is appended a list of 20 to 50 references. The work of some 400 authors is referred to, including that of Bradfield, Bauer, Jenny, and other soil scientists. The material is presented in a very attractive and lucid form. Every soil physicist and physical chemist will want a copy of this book for ready reference.

The Colloid Chemistry of the Silicate Minerals. By C. EDMUND MARSHALL. Academic Press, Inc., New York, 1949. Pp. 195, figs. 85. Price \$5.80.

The American Society of Agronomy is to be congratulated on having developed such an excellent monograph for the first in a series being published under the direction of a committee, of which A. G. Norman is chairman. The discussion

in this monograph is based primarily on studies of relatively pure materials rather than on such mixtures as occur in natural soils. It deals with fundamentals rather than with possible applications to practical agriculture. The 12 chapters present historical culture, introduction to silicate structures, three-dimensional frameworks, zeolites, planar frameworks, structural interpretation of chemical analyses, sizes and shapes of clay particles, optical properties, adsorption, clay acids, ion-exchange reactions, electrokinetic and mechanical properties of clays, and properties of clay aggregates and films. Reference is made to the work of some 225 workers in this field of research. The material is exceptionally well presented. The illustrations are excellent. The book is entitled to a prominent place on the shelf of every research specialist in soils.

Constructive Uses of Atomic Energy. Edited by S. C. ROTHMANN. Harper and Brothers, New York, 1949. Pp. 258, figs. 11. Price \$3.

The editor of this book has rendered a highly important service in pointing up the potentialities for good to be derived from atomic energy. The several authors deal with its present and possible uses for industrial power and in the fields of chemistry, metallurgy, aviation, ceramics, soil-plant research, biology, pharmacy, and medicine. The 14 chapters were written by an equal number of individuals and groups and present evidence of a highly impressive type of the developments in their several lines of work. The illustrations are of special interest. Three very important appendixes provide a chronological list of highlights significant to atomic energy, a glossary of important scientific terms, and a bibliography containing 323 titles. Since the material is presented in a relatively easily understood form, it is probable that the book will be widely read.

Encyclopedia of World Timbers. By F. H. TITMUS. Philosophical Library, New York, 1949. Pp. 156. Price \$4.75.

The purpose of this book is to provide a handy reference for those who are interested in the various kinds of wood and their adaptability for various purposes. The introductory chapter deals with the structure of wood, its identification, and some useful definitions. This is followed by specific descriptions and identification of some 200 timbers, arranged in alphabetical order. A bibliography of important books and research publications is appended. The index is by both botanical and trade names. The book has value for soil-plant scientists who are primarily concerned with forestry.

Experiments in Soil Bacteriology. By O. N. ALLEN. Burgess Publishing Co., Minneapolis, 1949. Pp. 126. Price \$2.50.

This offset-printed manual has a cardboard cover and ring binder. Designed for use in a one-semester 4-credit course, it gives detailed instructions about reading assignments, reagents, cultures, reports, and equipment and outlines 40 experiments. The three main divisions deal with a survey of soil microflora, microbial activities in the soil, and biological methods of determining mineral deficiencies. The main items under microbiological activities are nitrification,

sulfur and iron bacteria, hydrolysis and reduction, root-nodule bacteria, and digestion of cellulose. The appendix contains information on statistical methods, preparation of silica gel, tests for nitrates and potassium, nitrogen determination, testing rhizobia in the greenhouse, and preparation of cellulose dextrin. It is evident that much time and effort have gone into the preparation of this manual. Soil bacteriologists are certain to find it a very useful laboratory guide.

Fundamentals of Economic Geography. Revised edition. By NELS A. BENGTON AND WILLEM VAN ROYEN. Prentice-Hall, Inc., New York, 1947. Pp. 802, figs. 299. Price \$6.

The revised edition of this book is now in its nineteenth printing, which indicates that it is being widely used as a text. The chapters of most interest to soil-plant scientists are those dealing with population distribution, the earth, environment and human needs, introduction to the land, geographic importance of common rocks, land as a habitat of man, minerals of direct economic use, water-power resources, climates of the world, regions and products of the several climates, principal crop and animal industries of the several regions, economic significance of the sea, and the agrarian regions and related industrial developments. A set of selected references is given at the end of each chapter and a long list of publications that were consulted in the preparation of the book is shown in the appendix. The authors have presented a very interesting and instructive picture of geographical relationships. Much of the material is of considerable value for reference purposes to workers in agriculture.

General Chemistry. By A. W. LAUBENGAYER. Rinehart and Company, Inc., New York, 1949. Pp. 528, figs. 57. Price \$4.25.

Written for first-year college students, this textbook endeavors to provide a good background in chemistry for all science students. The material is very well presented and the tabular material and illustrations are well chosen. No references are given, so one is left to wonder what is the source of such highly interesting material as that in table 2 on the weight percentages of common elements in earth, atmosphere, sea water, soil, vegetation, and the human body. The author puts an interesting twist into occasional items, as when he points out that "when a liquid is distilled, its molecules are given a round trip from the liquid state to the vapor state and back to the liquid state." Evidently the periodic table and that of the atomic weights are considered to be of special importance, since they are repeated on the insides of the covers. One wonders why, in these days of visual instruction, the subheads are not made more specific. The book merits careful consideration for use in freshman chemistry.

Hydrology. Third impression. Edited by OSCAR E. MEINZER. Dover Publications, Inc., New York, 1949. Pp. 712. Price \$4.95.

Twenty-four specialists contributed to this symposium. It is number 9 of a series of monographs on physics of the earth, and was prepared under the direction of a committee of the National Research Council. The subjects covered are

precipitation, evaporation, snow, glaciers, lakes, infiltration, transpiration, soil moisture, ground water, runoff, droughts, physical changes produced by the water of the earth, hydrology of limestone terranes, and hydrology of lava-rock terranes. Many of the subjects discussed are of special interest to soil-plant scientists, and a number of the authors are identified with agricultural research institutions. Notable among these are George W. Musgrave, with an article on infiltration, Leonard D. Bayer, on retention and movement of soil moisture, and Harry R. Leach, on soil erosion. The other authors are engineers, geologists, physicists, and meteorologists with wide experience in their fields. The book is well illustrated, and each chapter is followed by a long list of references. A wide variety of scientists will find it of great interest and importance and will want copies close at hand.

Hydrology. By C. O. WISLER AND E. F. BRATER. John Wiley and Sons, Inc., New York, 1949. Pp. 419, figs. 132. Price \$6.

This book explains the procedures by which the minimum flow and long-term average yield of any drainage basin can be determined. It gives methods for computing the ground-water yield of wells, the flow that may be expected in a storm sewer, and the maximum flow that will occur in a watershed in a once-in-thousand-years' flood. It is of greatest interest to civil and agricultural engineering technicians and to soil physicists. The several chapters deal with the hydrograph, the drainage basin, precipitation, water losses, infiltration, ground water, runoff, floods, and stream-flow records. The book is modern in every respect and is entitled to a prominent place on the shelves of those who have to do with the more technical aspects of soil and water conservation in agriculture.

Interaction of Water and Porous Materials. Discussions of the Faraday Society, No. 3. Guernsey and Jackson, London, 1948. Pp. 294. Price 30s.

This paper-bound symposium report deals with the fundamental, botanical, and zoological aspects of the subject, permeability to water and water vapor of textiles and other fibrous materials, and oleophobic surfaces. The first two sections, comprising 168 pages, are of considerable interest to soil-plant scientists. Much of the theory of water movement, not easily available otherwise, is discussed by well-known authorities. Hitherto unpublished data are included in several papers. The theory of water movement in plants is particularly important to the man who desires further information on this subject. A general discussion follows each section, and the comments of a large number of prominent scientists in the several fields of research are included.

Ion Exchange Theory and Application. Edited by FREDERICK C. NACHOD. Academic Press Inc., New York, 1949. Pp. 411. Price \$8.50.

The book contains contributions from 16 industrial and university chemists who have done important work in this field of research and its practical application. The subjects treated are ion-exchange equilibria, kinetics of fixed-bed ion exchange, fundamental properties of ion-exchange resins, equipment de-

sign, water treatment, multistage systems, desalting sea water, applications to separation of inorganic cations, as a tool in analytical chemistry, metal concentration and recovery, catalytic applications, in biochemical and physiological studies, separation of amino acids by chromatography, sugar refining, recovery of alkaloids, and miscellaneous applications. Reference is made to the work of some 700 specialists in this field. Much of the material is of great interest and value to chemists who are concerned with ion-exchange relationships in soils. Workers in plant physiology will be especially interested in the part dealing with the purification of water. The book is entitled to and will have a very wide reading.

Manual of the Penicillia. By KENNETH B. RAPER AND CHARLES THOM. The Williams and Wilkins Company, Baltimore, 1949. Pp. 875, plates 10, figs. 172. Price \$12.

The authors examined some 4,000 strains of *Penicillia* in preparation for writing this volume. Their purpose is to aid in the rapid identification of these microorganisms in the laboratory. The necessity for this arose from the discovery of the usefulness of penicillin and its widespread production and use in the control of human diseases. The book is divided into three parts under general discussion, the manual proper, and reference material. The illustrations, including 10 plates in full color, are excellent and are a very important part of the volume. The bibliography is topical, under the headings: acid production, allergy, antibiotics, arsenic fungi, bulb and corn rots, cheese, deterioration and spoilage, enzymes, ergosterol, fat production, fruit rots, metabolic products, pathogenicity, penicillia in soil, penicillin, physiology, pigment production, polysaccharide production, and tannin. Reference is made to some 1,200 scientific papers. The chapter on penicillin, which deals with its discovery by Alexander Fleming in 1928 and the subsequent development of the product on a tremendous scale, makes especially interesting reading. The book is a highly useful reference work and represents a great deal of conscientious effort on the part of the authors, with highly important technical assistance from Dorothy I. Fennel.

Outlines of Biochemistry. Third edition. By ROSS AIKEN GORTNER. John Wiley and Sons, Inc., New York, 1949. Pp. 1078, figs. 124. Price \$7.50.

This revision was accomplished through the cooperation of former students and colleagues of the late Dr. Gortner, under the editorship of his two sons, Ross A. Gortner, Jr., and Willis A. Gortner. Because of the rapid developments in this field of research, much of the book had to be rewritten. New chapters on protein denaturation and on carbohydrate and lipid metabolism have been added. Some of the chapters have been materially condensed. The book is divided into six main parts: colloids, proteins, carbohydrates and related substances, lipids and essential oils, plant pigments, and biochemical regulators, including vitamins, hormones, and enzymes. Reference is made to the work of some 1350 authors. One of the most interesting parts of the book is the preface to the first edition. This outlines the various steps by which the original volume was developed. The

preface to the third edition brings this story down to date. It is apparent that no one man could have done all that was required to develop the great mass of details that are essential in such a comprehensive treatise. Those who have participated in the writing and rewriting of this book have rendered a highly important service to workers in this field of research. Both plant and animal scientists will find it a highly important addition to their reference shelves.

Oxidation Potentials. By WENDELL M. LATIMER. Prentice-Hall, Inc., 1938. Pp. 352. Price \$5.

The importance of oxidation potentials in soil-plant relationships is such as to justify drawing attention to this book even though it was published 10 years ago. The book gives the units, conventions, and methods employed, discusses ionization potentials, electron affinities and lattice energies, and then deals specifically with H, O, Cl, S, N, C, Ga, Zn, Cu, Ni, Co, Fe, Mn, Cr, V, Ti, B, Mg, K, and the elements that are closely related to each of these. The appendix gives summaries of oxidation-reduction potentials, free energies of formation, equilibrium constants, activity of strong electrolytes, entropy values, and 142 important references related thereto.

Potato Production. By E. V. HARDENBURG. Comstock Publishing Company, Inc., Ithaca, New York, 1949. Pp. 270, figs. 129. Price \$3.

The author has devoted his entire career to this crop and, as a result, has a wide acquaintance both with the science and the practice of potato production. This is well revealed in his carefully documented book, which begins with a chapter on the economic importance of potatoes, and then deals with botany and plant development, climate and soil relationships, rotation, soil management, fertilization, seed, planting, cultivation, varieties, diseases, insects, tuber defects, harvesting, storage, grading, marketing, quality, use, breeding, and economics of production, as applied to this crop. The illustrations are well chosen. A list of references is appended to each chapter. The book is an exceptionally good example of superior craftsmanship and should enjoy a wide sale.

Practical Analysis, Graphical and Numerical Methods. By FR. A. WILLERS. Translated by Robert T. Beyer. Dover Publications, Inc., New York, 1948. Pp. 422, figs. 132. Price \$6.

The author of this book is professor at the Freiberg Mining Academy, at Charlottenburg, Germany. His work in numerical, graphical, and instrumental methods of practical analysis is widely recognized. The problem is to employ the method that gives most readily the degree of accuracy required. The first chapter deals with approximate values and the use of slide rules and calculating machines. The remaining chapters are concerned with interpolation, integration and differentiation, practical equation theory, analysis of empirical function, and approximate integration of ordinary differential equations. The book should be available for reference by those concerned with statistical analyses and the interpretation of large masses of data.

Recent Advances in Analytical Chemistry. Edited by R. E. BURK AND OLIVER GRUMMITT. Interscience Publishers, Inc., New York, 1949. Price \$4.50.

This is volume 7 of *Frontiers in Chemistry*, published under the auspices of Western Reserve University. The collaborators are I. M. Kolthoff, John H. Yoe, Otto Beeck, James Hillier, Frederick D. Rossini, and J. A. Hipple, who are introduced by photographs and life histories. The text is divided into seven main parts. These deal with voltammetry and amperometric titrations; inorganic analyses with organic reagents; recent colorimetric and gravimetric organic reagents; application of infrared spectroscopy in analysis; electron microscopy and microanalysis; fractionation, analysis, and purification of hydrocarbons; and applications of the mass spectrometer. A well-developed list of references is appended to each part. The book contains such a variety of material of such new and interesting import as to make it useful to a great variety of chemists. Almost any analyst will find something of great importance to him in his work.

Reconnaissance Soil Survey of Japan, Kanto Plain Area, Report No. 110-A. By MORRIS E. AUSTIN, C. L. W. SWANSON, W. S. LIGON, WILLIAM D. LEE, AND T. E. RITCHIE. General Headquarters Supreme Commander for the Allied Powers, National Resources Section, Tokyo, 1948. Pp. 68.

The Kanto Plain Area lies to the north of Yokohama and Tokyo Bay, an area of 32,127 square kilometers. This is the largest and most important agricultural area of Japan and has been so for many centuries. The population is over 15 million people, of which about 32 per cent are engaged in agriculture. The most important crop is rice, but large amounts of wheat, barley, potatoes, and sweet potatoes are also grown. The soils are young, with weakly developed profiles. The Brown Ando soils, with dark brown surface layers and yellowish brown silty subsoils, are the most important group. The general nature of the area, its agriculture, and its forestry are also dealt with in this report. One large plate shows the physical characteristics and use of the soil associations in that area. The report includes a set of soil maps in color. It should be of special interest to those who deal with problems of soil classification and land use.

Soil Mechanics in Engineering Practice. By KARL TERZAGHI AND RALPH B. BECK.

John Wiley and Sons, Inc., New York, 1949. Pp. 566, figs. 218. Price \$5.50.

The book is divided into three parts. The first deals with physical properties of soils, the second with theoretical soil mechanics, and the third with problems of design and construction. Since the applications are in fields other than agriculture, the approach is quite different. Yet many points of much interest to soil-plant scientists are discussed. A good example is found under the heading of "frost heave and frost-heave prevention." In this it is pointed out that ice layers form only in fine-grained soils. Once the layers start to form, water tends to flow toward them from below, just as it does if water is withdrawn from the topsoil by plants. The rate and distance of flow depend upon the size distribution of the subsoil particles. Other similarly interesting points are developed, in other portions of the book. Reference is made to the work of some 150 authors. The book is entitled to a place on the shelf of every soil physicist.

The Soils of Palestine. Revised second edition. By A. REIFENBERG. Translated by C. L. Whittles. Murby and Co., London, 1947. Pp. 179. plates 18. Price 16s.

"For fifteen hundred years the land has steadily deteriorated," is the beginning sentence in this book. Later on the author writes: "The Palestine we see today is but the ruin of a once-flourishing country." At another point is the statement: "It should not be forgotten that many problems, as for example restrictions on the grazing of goats, are closely linked up with economic questions." The author, who is lecturer on agricultural chemistry and soils in the Hebrew University, Jerusalem, has spent some 25 years in the study of the soils of Palestine. In the book he deals with geology, relief, moisture, and climate, soil formation, the evolution and characteristics of the soils of the arid, semiarid, semihumid, and humid regions, soil formation under Mediterranean climate as compared with that under other climates, soils and agriculture, erosion, and the Jordan Valley Authority. Important references are appended to each chapter. The book should be of much interest to a great many persons, from both the technical point of view and that of understanding the problems involved in fully regenerating the agriculture of that country.

THE EDITORS.

TABLE 2
Citric and oxalic acid contents of green and chlorotic citrus leaves
 Dry-matter basis

SAMPLE NUMBER	VARIETY	LEAF	CITRIC ACID	OXALIC ACID
			mgm./gm.	mgm./gm.
750	Grapefruit	Green	19.3	55.2
751	Grapefruit	Chlorotic	15.4	53.5
1064	Grapefruit	Green	16.8	53.7
1066	Grapefruit	Chlorotic	15.9	51.6
1057	Lemon	Green	2.9	65.5
1058	Lemon	Chlorotic	2.7	46.5
745	Valencia	Green	15.0	46.9
746	Valencia	Chlorotic*	17.0	34.4
747	Valencia	Chlorotic†	20.6	20.2
1061	Valencia	Green	19.7	42.1
1062	Valencia	Chlorotic*	26.5	30.3
1063	Valencia	Chlorotic†	25.5	32.6
1072	Valencia	Green	18.3	43.0
1073	Valencia	Chlorotic*	20.4	31.1
748	Valencia	Green	14.3	43.4
749	Valencia	Chlorotic*	17.0	34.2
1067	Valencia	Green	34.2	39.2
1068	Valencia	Chlorotic†	56.5	31.2
1069	Valencia	Green	29.0	41.6
1070	Valencia	Chlorotic*	31.2	33.3
1071	Valencia	Chlorotic†	47.2	31.8
1074	Grapefruit	Green	24.4	38.7
1075	Grapefruit	Chlorotic†	26.5	28.5
1082	Grapefruit	Green	12.9	63.5
1083	Grapefruit	Chlorotic*	15.8	55.8
1084	Grapefruit	Green	12.5	71.9
1085	Grapefruit	Chlorotic*	15.8	59.4

* Iron-deficiency chlorotic pattern.

† Zinc-deficiency chlorotic pattern.

CITRUS STUDIES

Samples of green and chlorotic citrus leaves from 10 different groves were analyzed for citric and oxalic acids. The analyses are given in table 2. All but two cases show excellent agreement with Iljin's findings. Citric acid content of

the chlorotic leaves is higher than that of the green leaves for all matched samples except the lemon and grapefruit leaves from a grove where there was additional leaf injury from excess boron. It is significant that the difference between green and chlorotic leaves is not so great as that found by Iljin for the plants he examined. The oxalic acid values for green and chlorotic citrus leaves appear to be more consistent than the citric acid values. Apparently, chlorosis in citrus is ac-

TABLE 3

Citric acid, oxalic acid, and active iron contents of green and chlorotic leaves from deciduous fruit trees*

Dry-matter basis

SAMPLE NUMBER	FRUIT	LEAF	CITRIC ACID	OXALIC ACID	ACTIVE Fe
			mgm./gm.	mgm./gm.	per cent†
1092	Peach	Green	2.5	63.3	....
1090	Peach	Chlorotic	11.5	48.1	....
1112	Peach	Green	11.8	69.7	.011
1113	Peach	Chlorotic	22.2	49.8	.009
1154	Peach	Green‡	8.1	61.6	.014
1114	Peach	Green	8.5	77.6	.014
1115	Peach	Chlorotic	29.0	44.0	.012
1155	Peach	Green‡	13.7	52.2	.014
1127	Peach	Green	6.9	80.0	.017
1128	Peach	Chlorotic	18.8	54.1	.021
1147	Peach	Green‡	8.1	61.6	.014
1143	Peach	Green	2.7	81.5	....
1144	Peach	Chlorotic	13.0	33.7	....
1116	Plum	Green	4.7	93.0	....
1151	Apple	Green‡	11.2	50.5	.024
1152	Apple	Green	13.0	49.5	.011
1153	Apple	Chlorotic	23.1	32.7	.009

* The chlorotic pattern was that identified as iron deficiency.

† Of total iron content soluble in *N* HCl.

‡ From a branch plugged with ferric citrate.

accompanied by a reduction in oxalic acid and an increase in citric acid in leaves, and this is true for both the iron- and zinc-deficiency patterns.

In all groves, green and chlorotic leaves of each group of matched samples were taken from the same tree.

STUDIES ON DECIDUOUS FRUITS

Samples of green and chlorotic leaves were collected from a number of deciduous orchards. The analyses, given in table 3, agree very closely with those pub-

lished by Iljin. In every case the chlorotic leaves are higher in citric acid than the green leaves, and the difference is greater than that between the green and chlorotic citrus leaves. Without exception, the oxalic acid content is lower in the chlorotic leaves. The highest oxalic acid value is significant. This sample, 1116, was taken from a plum tree which showed no chlorosis and was growing alongside the severely chlorotic peach trees from which samples 1112 and 1113 were taken. The analysis of sample 1116 emphasizes the importance of a proper balance of citric and oxalic acids in leaves of deciduous fruit trees.

In late July a number of trees were "plugged" with ferric citrate according to the method suggested by Bennett (1). Only on the trees that were heavily watered after the injection did the plugged branches recover their normal green color. In mid-October, when this recovery was complete, leaf samples were taken from some of the trees. It is significant that the ferric citrate injection reduced the citric acid and increased the oxalic acid in the leaves in all cases, and it increased the active iron in several instances.

STUDIES OF LUPINES

The analyses of leaf samples presented in tables 1, 2, and 3 show two major factors that are associated with lime-induced chlorosis in Arizona. These are a low activity or mobility of iron within the plant and an unbalanced citric-oxalic-acid relationship. As already shown, the latter association apparently does not apply for monocotyledons—at least for Sudan grass and hegari leaves, the ash of which is siliceous. The highly calcareous soils in which the crops are grown probably contribute to the two factors by rapidly neutralizing the root secretions which normally maintain a zone of acidity where the soil is in contact with the feeding zone of the root.

As shown in the section on field crops, the chlorotic hegari plants were restored to normal green color by side-dressing with a band of sulfur-manure mixture. Similar response has been obtained with young chlorotic citrus trees, citrus seedlings, and grain seedlings (4, 5) when it is possible to bring the mixture into contact with the roots. Less success has been attained with old trees the roots of which have retired to lower soil horizons.

Iljin (2, 3) and Schander (9, 10, 11) found a distinctive difference in tolerance of white, blue, and yellow lupines for the soil conditions that produce lime-induced chlorosis. As shown in the section on deciduous fruits, when the chlorosis was corrected by plugging the trees with iron citrate, citric acid was reduced and oxalic acid increased in the leaves. Greenhouse experiments (4, 5) with grain and citrus seedlings have shown that application of sulfur and iron sulfate to calcareous soils increases activity of iron in the plant and corrects chlorosis.

In view of these findings, a number of pot experiments were conducted with lupines to study the effect of acidifying agents on citric acid in leaves. Three of these experiments have been selected to show the results of this study.

Experiment 1

For this experiment two soils were selected, one containing 10.5 per cent CaCO_3 and the other 1.94 per cent. Thirty-six pots, each filled with 2 kilos of soil, were

set up for each. The group of 36 was divided into 12 controls; 12 which received an application of sulfur at the rate of 2 tons per acre; and 12 which received an application of sulfur-manure mixture, such as that used in the field crop studies, at the rate of 4 tons per acre. Each set of 12 was further divided into 4 pots for white lupine, 4 for blue lupine, and 4 for yellow lupine. The plants were grown for 2 months and then harvested for analysis. The yellow lupine plants made such poor growth that they were discarded. Roots and tops of plants were analyzed separately. The analyses are given in tables 4 and 5.

TABLE 4
Analysis of tops of white and blue lupines from experiment 1
Dry-matter basis

SAMPLE NUMBER	PLANT	TREAT- MENT*	CITRIC ACID	ACTIVE Fe	TOTAL Ca	TOTAL Mn	TOTAL Zn	TOTAL Cu
			mgm./gm.	per cent	per cent	per cent	per cent	per cent
Highly calcareous Mesa soil								
1186	White	1	14.1	.006	1.76	.035	.010	.006
1188	White	2	13.2	.010	1.50	.039	.010	.005
1190	White	3	14.5	.014	2.18	.078	.010	.003
1192	Blue	1	76.0	.004	4.48	.014	.012	.011
1194	Blue	2	11.9	.007	3.33	.015	.020	.005
1196	Blue	3	26.2	.008	4.05	.035	.025	.006
Slightly calcareous Marana soil								
1198	White	1	17.3	.005	1.36	.048	.006	.003
1200	White	2	6.3	.008	0.48	.114	.006	.003
1202	White	3	7.6	.006	2.09	.114	.018	.003
1204	Blue	1	57.8	.005	2.91	.009	.017	.004
1206	Blue	2	6.7	.006	3.36	.068	.010	.004
1208	Blue	3	19.3	.005	3.22	.065	.026	.003

* Treatments: 1, controls; 2, fertilized with sulfur; 3, fertilized with sulfur and manure

The difference between white and blue lupines in their tolerance toward the different amounts of CaCO_3 in these two soils is clearly shown in this experiment, as is also the relation between the citric acid content, calcium uptake, and activity of the iron. Tests for oxalic acid on all plant samples showed only insignificant traces.

Citric acid. In agreement with Iljin, less citric acid was found in the white than in the blue lupine, which is less tolerant of a calcareous substrate. In the highly calcareous soil the acidifying agents had no effect on citric acid in the white lupines, but the sulfur significantly reduced the citric acid in the slightly calcareous soil. This indicates that the amount of sulfur applied to the highly calcareous soil was not sufficient to effect a reduction in citric acid. In the blue

lupine, which contains large amounts of citric acid when grown in a calcareous substrate, the sulfur reduced citric acid significantly.

Active iron. Both percentage of active iron and percentage active of total iron (active Fe/total Fe) were increased in all cases by sulfur. Total iron in the roots was decreased by sulfur. This is in agreement with other of our experiments showing that plants require more iron when growing in calcareous soils and that total uptake is less when the activity in the plant is increased. The higher total

TABLE 5
Analysis of roots of white and blue lupines from experiment 1
Dry-matter basis

SAMPLE NUMBER	PLANT	TREATMENT*	TOTAL Fe	TOTAL Ca	TOTAL Mn	TOTAL Zn	TOTAL Cu
			per cent	per cent	per cent	per cent	per cent
Highly calcareous Mesa soil							
1187	White	1	.166	1.69	.008	.018	.013
1189	White	2	.124	3.34	.007	.013	.009
1191	White	3	.133	3.52	.014	.037	.007
1193	Blue	1	.256	2.86	.011	.041	.014
1195	Blue	2	.239	4.57	.011	.014	.009
1197	Blue	3	.212	9.37	.052	.072	.016
Slightly calcareous Marana soil							
1199	White	1	.072	1.50	.012	.016	.017
1201	White	2	.044	2.69	.023	.016	.018
1203	White	3		3.24	.027	.049	.025
1205	Blue	1	.200	4.48	.015	.064	.022
1207	Blue	2	.076	4.10	.020	.010	.008
1209	Blue	3	.062	7.11	.121	.103	.009

* Treatments: 1, controls; 2, fertilized with sulfur; 3, fertilized with sulfur and manure.

iron in the roots of blue lupine indicates lesser mobility than in the white and this may be one reason for the greater susceptibility of blue to chlorosis.

Calcium. The calcium data are extremely significant, especially the analyses showing the higher calcium percentage in both roots and tops of the less tolerant blue lupine. This high calcium percentage correlates with higher citric acid and lower percentage of active iron. The presence of an acidifying agent in the soil reduced the citric acid, increased the active iron, and corrected the chlorosis even in the presence of a high calcium uptake. Calcium uptake by the white lupines was also increased by sulfur, but in the presence of a greater iron activity in the plant there was no chlorosis. This indicates that if sufficient iron activity can be maintained in the plant the high calcium uptake is not harmful and will not cause an increase in citric acid as it did in the controls.

Manganesec, zinc, and copper. In agreement with other experiments conducted



FIG. 1. GROWTH OF WHITE AND BLUE LUPINES IN SLIGHTLY CALCAREOUS SOIL

1, white lupine control; 2, blue lupine control; 3, white lupine with sulfur treatment; 4, blue lupine with sulfur treatment; 5, white lupine with sulfur manure treatment; 6, blue lupine with sulfur manure treatment



FIG. 2. GROWTH OF WHITE AND BLUE LUPINES IN HIGHLY CALCAREOUS SOIL

1, white lupine control; 2, blue lupine control; 3, white lupine with sulfur treatment; 4, blue lupine with sulfur treatment; 5, white lupine with sulfur-manure treatment; 6, blue lupine with sulfur-manure treatment



FIG. 3. GROWTH OF WHITE AND BLUE LUPINES IN ACID AND CALCAREOUS SOILS

1 and 2, white lupines in acid soil; 3, white lupine in calcareous soil; 4 and 5, blue lupine in acid soil; 6, blue lupine in calcareous soil

with these calcareous soils (4, 5), increased uptake of manganese, zinc, and copper is easily attained by incorporation of acidifying agents with the soil. In fact, the excessive uptake of manganese and zinc was harmful in this experiment, as shown in figures 1, 2, and 3. This is in contrast to iron, in that addition of sulfur

and the sulfur-manure mix containing iron sulfate reduced total iron uptake. The increase was in iron activity and not in total iron.

Experiment 2

This experiment was designed to study the effect of increasing amounts of sulfur added to a soil containing 6.6 per cent CaCO_3 . The series of treatments included controls and soil to which 2, 4, 6, and 8 gm. of sulfur per 2 kgm. of soil were added. Each was triplicated, making 15 pots in all. White lupines only

TABLE 6

Effect of increasing amounts of sulfur on citric acid, manganese, and active iron contents of white lupine tops

Dry-matter basis

SAMPLE NUMBER	SULFUR/2 KOM.	CITRIC ACID	ACTIVE IRON	MANGANESE
	gm.	mgm./gm.	per cent	per cent
1214		12.8	.005	.095
1216	2	10.5	.006	.134
1217	4	12.3	.006	.136
1218	6	10.6	.007	.156
1219	8	8.3	.007	.160

TABLE 7

Citric acid content of white and blue lupines in acid and calcareous soils

SAMPLE NUMBER	PLANT	SOIL	CITRIC ACID
			mgm./gm.
1210	White	Acid	8.3
1212	Blue	Acid	7.4
1226	White	Calcareous	12.1
1229	Blue	Calcareous	34.1

were used in this experiment. They were grown for 6 weeks. The tops were then removed and analyzed for citric acid, active iron, and total manganese (table 6).

This experiment adds confirmation to the data given for the first experiment with lupines. Percentage active iron and manganese uptake are increased and citric acid is decreased with increasing amounts of sulfur added to the soil.

Experiment 3

This experiment shows the comparative growth of white and blue lupines in acid and calcareous soils. The acid soil had a pH of 6.5, and the calcareous soil contained 10.5 per cent CaCO_3 . The plants were grown for 54 days and then analyzed. The data in table 7 show that both white and blue lupines in acid soil contained less citric acid than those in calcareous soil.

SUMMARY

Lime-induced chlorosis exist on both orchard and field crops growing on Arizona calcareous soils. The chlorotic pattern is predominantly of the iron-deficiency type.

Green and chlorotic leaves from a number of orchard and field crops in Arizona were analyzed to determine particularly whether any correlation exists between citric and oxalic acids and active iron in lime-induced chlorosis.

For field crops less active iron was found in chlorotic leaves than in green leaves. Higher citric acid was found in the chlorotic leaves of dicotyledons, and this was associated with less active iron. No such relation was found for the two monocotyledons hegari and Sudan grass. An oxalic acid relationship was also noted for the dicotyledons: chlorosis reduced the oxalic acid content of leaves.

For leaves of citrus and deciduous fruits, a marked correlation was found between active iron, citric acid, and oxalic acid: chlorotic leaves contained less active iron, less oxalic acid, and more citric acid than did green leaves.

It has been shown that chlorosis can be controlled successfully with acid soil correctives if contact can be made with the root system. The fundamental value of these correctives was shown in the effect upon hegari in the field and upon lupines grown in pots. It is significant that, in correcting chlorosis by this method, active iron in the plant was increased in both the monocotyledons and the dicotyledons but that citric acid was reduced only in the dicotyledons. There is little or no tendency for hegari to build up citric acid in chlorotic leaves. Injection of iron citrate produced the same effect on apple and peach leaves as did sulfur additions to the soil for hegari and lupines; namely, increase in active iron, increase in oxalic acid, and decrease in citric acid.

REFERENCES

- (1) BENNETT, J. P. 1931 The treatment of lime-induced chlorosis with iron salts. Calif. Agr. Exp. Sta. Cir. 321.
- (2) ILJIN, V. S. 1943 Metabolism of the grapevine during lime chlorosis. *Gartenbauwiss.* 17: 328-381. (Abstract in *Chem. Abs.* 38: 6332. 1944.)
- (3) ILJIN, V. S. 1944 Salts and organic acids in relation to calciophiles. *Flora* 37: 265-299. Abstract in *Chem. Abs.* 39: 4113. 1945.)
- (4) McGeorge, W. T. 1948 Nutrient interrelations in lime-induced chlorosis as revealed by seedling tests and field experiments. *Ariz. Agr. Exp. Sta. Tech. Bul.* 116.
- (5) McGEORGE, W. T. 1949 A study of lime-induced chlorosis in Arizona orchards. *Ariz. Agr. Exp. Sta. Tech. Bul.* 117.
- (6) OSERKOWSKY, J. 1933 Quantitative relations between chlorophyll and iron in green and chlorotic leaves. *Plant Physiol.* 8: 449.
- (7) PUCHER, G. W., VICKERY, H. B., AND WAKEMAN, A. J. 1934 Determination of acids of plant tissue: II. Total organic acids of tobacco leaf. *Indus. and Engin. Chem., Analyt. Ed.* 6: 140.
- (8) PUCHER, G. W., VICKERY, H. B., AND LEAVENWORTH, C. S. 1934 Determination of acids of plant tissue: III. Determination of citric acid. *Indus. and Engin. Chem., Analyt. Ed.* 6: 190.
- (9) SCHANDER, H. 1939 The dependence upon external factors of chlorosis of *Lupinus luteus* seedlings in sand cultures. *Bodenk. u. Pflanzenernähr.* 12: 71-84. (Abstract in *Chem. Abs.* 33: 2942.)
- (10) SCHANDER, H. 1943 The differences and similarities of chlorosis in lupines and wood growths. *Gartenbauwiss.* 17: 304-309. (Abstract in *Chem. Abs.* 38: 6332. 1944.)
- (11) SCHANDER, H. 1943 The problem of lime chlorosis in plants. *Jahrb. Wiss. Bot.* 91: 169-185. (Abstract in *Chem. Abs.* 39: 4649. 1945.)

ANION SORPTION AND EXCHANGE BY AMINE-CLAY COMPLEXES

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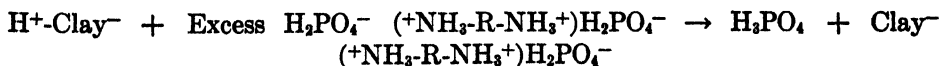
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The importance of the cation exchange reactions of soil clays in the nutrition of plants has been demonstrated by many investigators. A somewhat parallel importance of anion exchange by constituents of soil clays has been assumed by several investigators. Most of the work on anion exchange reactions of clays has been concentrated on studies involving the phosphate ions, chiefly because of the widespread response of soils to phosphate fertilization and because of the complexities of phosphate-soil-plant relationships.

The work of Bray and Dickman (3), Coleman (4), Dean and Rubins (5), Dickman and Bray (6), Ensminger (9), Kelly and Midgley (13), Kurtz, DeTurk, and Bray (15), Low and Black (16), Mattson (18), Murphy (19), Nitzsch and Czeratski (20), Perkins (21), Ravikovitch (22), Scarseth (23), Sieling (24), Stout (25), and Toth (26) shows that minerals common to soil clays exhibit anion exchange reactions. McAuliffe *et al.* (17) showed conclusively by the use of "tagged" ions that the hydroxyl ions of kaolinite and hydrated iron and aluminum oxides could be exchanged by other anions.

The results of investigations on the role of soil organic constituents as anion exchangers are conflicting. Aderikhin (1) found that humus sorbed phosphate ions from monocalcium phosphate, whereas Doughty (7) found that soil organic matter did not play an important part in fixing phosphates. Synthetic organic resins containing free amino groups have been found to exhibit anion exchange. The mechanism of exchange in these resins was investigated by Griessbach (11), Kunin and Myers (14), and Wiklander (27), who showed that the amino groups are responsible for the anion exchange capacity.

Since the anion exchange resins sorb and exchange anions through free amino groups, it seemed reasonable that polyamino organic soil complexes and polyamino clay complexes might exhibit anion sorption and exchange. Investigations by Bradley (2), Ensminger and Giesecking (8), Giesecking (10), and Hendricks (12) on organic clay complexes have shown that basic nitrogenous organic compounds are very strongly sorbed on clays. It was thought that while some of the amino groups of polyamino compounds hold these large cations to the clay surface, others might be left free to exhibit anion sorption and exchange similar to the polyamine resins as shown in the following reaction:



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The present study was planned to investigate the role of some nitrogenous organic clay complexes and soil organic matter in anion sorption and exchange reactions.

The availability of radiophosphorus provided a method by which the relationship between anions and the amino-clay complexes could be conveniently studied, especially if the amounts of phosphorus to be measured should fall in the micro-range. The use of this technique also permitted a precise phosphorus analysis on clay suspensions themselves, which could not have been performed by the usual quantitative procedures without destruction of the clay minerals before the analysis. The radioactive isotope of phosphorus was used as a tracer because of the importance of phosphorus-soil relationships in plant nutrition. Furthermore, radiophosphorus has a satisfactory half-life (14.3 days), and it decays by emitting beta particles with sufficient energy (1.69 mev.) for convenient measurement.

PHOSPHATE EXCHANGE BY MONTMORILLONITE-AMINE COMPLEXES

Three amino-clay complexes were prepared by mixing solutions of the hydrophosphates of diethylene triamine, of paraphenylene diamine, and of pyridine with $<2\text{-}\mu$ montmorillonite suspension. The hydrophosphates were prepared by adding three equivalents of a constant ratio phosphoric acid solution to one equivalent of amine. The constant-ratio phosphoric acid solution was prepared by adding 1.5 ml. of radiophosphoric acid (1.76 millicuries) to 25 ml. of concentrated inactive phosphoric acid. All subsequent phosphate solutions used in this investigation were made from this original solution. The $<2\text{-}\mu$ montmorillonite suspension was prepared from Wyoming bentonite, which had a cation exchange capacity of 1 me. per gram. The final step in the preparation of the complexes was to add 5 me. of each of the amine hydrophosphates to 1 gm. of clay in suspension. This five-to-one excess of amine was added to ensure as complete saturation of the base exchange capacity of the clay as possible by single amino groups from the polyamine cations.

The flocculated amine-phosphate-clay suspensions were vigorously shaken and divided into 10 homogeneous 100-ml. aliquots for washing and replacement studies. Wash solution, containing 1.6 me. of H_2PO_4^- per liter, sufficient for all subsequent experiments was prepared from the constant-ratio radioactive H_2PO_4^- solution and was used instead of pure water to suppress removal of sorbed phosphate ions by hydrolysis. Several pilot experiments showed washing by four cycles of alternate centrifugation, decantation, and dispersion to be more convenient and slightly more effective than 10 washings by filtration. Duplicate 100-ml. aliquot portions of the amine-phosphate-clay suspensions were, therefore, washed through the four cycles. The amine-phosphate-clay floccules were finally thoroughly dispersed in 50 ml. of the radioactive wash solution to which 0.25 gm. of NaOH had been added to peptize the clay complex. After complete dispersion, the suspension was again made up to 100 ml. with the radioactive wash solution. The radioactivity of this suspension was then compared with that of the wash solution, which served as a control for decay of active phosphorus during the course of the investigation and as a standard for phosphate concentrations.

The radioactivities of all solutions and suspensions used in this investigation were measured in a single annular ring type of vessel placed around a Geiger-Müller upright tube. In this way constant volumes of all suspensions and solutions and constant geometry of all samples, with respect to the Geiger-Müller tube, were assured for all measurements.

In the experiments in which the phosphated samples were washed with water containing 1.6 me. of H_2PO_4^- , the differences between the activity of phosphated samples suspended in the wash water and the activity of the wash water were used to calculate the phosphate sorbed on the clay-amine complexes. Since the ratio of inactive to active phosphorus was the same in both the wash solution and the more concentrated solution originally used to react with the clay-amine complexes, these differences represent the failure of the wash solution to reduce the phosphate on the complexes to levels equal to that of the wash solution. This is assumed to be sorbed phosphate, which is insoluble in water.

TABLE 1

Retention of phosphate by three amine-montmorillonite complexes and by untreated and aminized muck

AMINE	PHOSPHATE RETAINED		
	Washed with H_2O	Washed with N HNO_3	Washed with $\text{N H}_2\text{SO}_4$
	me./100 gm	me./100 gm.	me./100 gm.
Pyridine	5.6*	4.4	1.6
Paraphenylene diamine.....	14.7*	10.5	3.0
Diethylene triamine.....	24.5*	10.4	5.5
Untreated muck.....	1.3		Tr.
Aminized muck.....	7.7		5.5

* Wash water contained 1.6 me. of H_2PO_4^- per liter, which was subtracted as a blank.

Since a considerable quantity of phosphate was retained by the amine-clay complexes (table 1), the ease of release of the sorbed phosphate was tested. This was accomplished by placing duplicate 100-ml. aliquots of the amine-phosphate-clay complexes in equilibrium with 100 ml. of N HNO_3 and with 100 ml. of $\text{N H}_2\text{SO}_4$, respectively, for 24 hours. The clay complexes were washed with the normal acid solutions through four cycles of centrifugation, decantation, and dispersion. They were dispersed in 100 ml. of the normal acid solutions after they were made alkaline with NaOH . The radioactivity of these solutions was then compared with that of the standard radioactive wash solution, and the amounts of phosphate remaining on the amine-clay complexes were calculated.

EFFECT OF FREE AMINO GROUPS IN SOIL ORGANIC MATTER ON PHOSPHATE SORPTION

This experiment was designed to show the effects of free amino groups, if any were present in the organic fraction of the clays, upon phosphate sorption. Wabash clay (a black clay) and Jacob clay (a gray clay) were compared with respect to their phosphate-sorbing capacities before and after destruction of any

free amino groups by nitrous acid. Suspensions of these clays were freed of sands by decantation. The clays were treated with 13 me. of H_2PO_4^- per gram of clay. Replicates which were deaminized received 0.35 gm. of NaNO_2 to generate HNO_2 .

One-hundred-milliliter aliquots of the untreated and the nitrous-acid-treated Wabash and Jacob clay suspensions were washed, by four cycles of centrifugation and decantation, with the constant-ratio wash solution containing 1.6 me. of H_2PO_4^- per liter. The clays were suspended in the wash solution. The difference between the activities of these clay suspensions and the activity of the constant-ratio wash solution was used as a measure of the amount of phosphate sorbed by the clays before and after deaminization. The exchangeability of this sorbed phosphate was then tested using HSO_4^- in $N \text{ H}_2\text{SO}_4$ as the replacing ion. One-hundred-milliliter aliquots were washed with $N \text{ H}_2\text{SO}_4$ through four cycles of alternate centrifugation and decantation. The suspensions were dispersed with NaOH and their activities measured. The results of this experiment are shown in table 2.

PHOSPHATE EXCHANGE BY MUCK

To study more closely the role of soil organic matter in anion sorption, an attempt was made to determine the amount of phosphate sorbed by muck. Also, it was thought that the anion exchange capacity of a muck might be increased by creating strongly basic quaternary ammonium compounds in the muck by a series of organic reactions. One hundred grams of muck was nitrated with a solution of 7.8 $N \text{ HNO}_3$. It was washed by decantation and treated with SnCl_2 and HCl in an attempt to reduce any nitro groups to amino groups. This material was washed and placed in a methanol solution containing K_2CO_3 and reacted with methyl iodide to produce the corresponding quaternary ammonium compounds. Five-gram samples of this material and 5 gm. of the untreated muck were each reacted with a 50-ml. solution containing 1.559 gm. of H_3PO_4 with some radioactive H_3PO_4 present as a tracer. The samples were then washed on filter paper with distilled water and dispersed in a known volume containing 0.5 gm. of NaOH . The activity was compared with that of a standard which contained the same ratio of radioactive H_3PO_4 to inactive H_3PO_4 as the samples. When considerable quantities of H_3PO_4 were found to be retained, steps were taken to test the exchangeability of the specially aminized muck. The material was precipitated with $N \text{ H}_2\text{SO}_4$, washed on filter paper with $N \text{ H}_2\text{SO}_4$, redispersed with NaOH , and the activity again compared with that of the standard. The results are given in table 1.

EFFECT OF DRYING ON ANION EXCHANGE

Several attempts were made to exchange anions sorbed on polyamine-clay complexes after the complexes were dried. Benzidine, *o*-phenylene diamine, *p*-phenylene diamine, and gelatin were the amines used in the complexes. The chloride salt of benzidine and the sulfate salts of the others were reacted with montmorillonite suspensions, washed, dried, and ground. Various anions were used in an attempt to replace the chloride and sulfate ions. Chloride was deter-

mined by the Volhard method and the sulfate by BaSO_4 precipitation. No exchange could be observed.

Samples of the previously discussed diethylene triamine, montmorillonite complex, Wabash clay, and Jacob clay were tested to see whether, after drying, the radioactive phosphate could be exchanged. One-hundred-milliliter aliquots of the above suspensions from the original phosphoric-acid-treated samples were dried 24 hours in an oven at 100°C . without removal of any of the excess phosphoric acid remaining in solution. They were washed with NH_4SO_4 by filtration to remove all the phosphate possible. The samples were then dispersed with NaOH , made up to the original 100-ml. volume, and their activities measured. Amounts of phosphate retained by the dried samples and the corresponding suspensions were determined by comparison with the radioactive standard (table 3).

DISCUSSION OF RESULTS

Polyamine-clay complexes seem to be able to sorb and exchange anions, as indicated in table 1. Since the triamine complex sorbed more than the diamine and the diamine more than the monoamine, it appears that the amount of phosphate sorbed is directly related to the number of amino groups present per molecule of amine. In determining the anion capacity, these complexes were washed with distilled water containing 1.6 ml. per liter of H_2PO_4 to suppress hydrolysis of the sorbed phosphate and to reduce the competition of traces of any foreign anions that might be found in the distilled water.

The nitrate and sulfate anions replaced significantly large amounts of the phosphate, as shown in table 1. The fact that sulfate was more efficient in replacing the phosphate than was the nitrate agrees with Kunin and Myers' (14) order of replacing ability of anions on polyamine resins.

The experiment with Wabash and Jacob clays indicates considerable phosphate sorption by both, with no significant difference between the clay high in organic matter and the clay low in organic matter (table 2). The capacity of the deaminized samples of each type of clay for phosphate sorption did not differ significantly from that of the untreated samples. This, together with the fact that untreated muck has a low capacity (table 1), indicates that soil organic matter, as such, does not play a large part in anion sorption and exchange. This agrees with Doughty's (7) work on organic matter as influencing phosphate fixation.

Large amounts of phosphate were sorbed by the two soil clays. Some of the phosphate could be exchanged with NH_4SO_4 as shown in table 2. It is interesting to note that these clays retained large amounts of phosphate that could not be replaced by $\text{N H}_2\text{SO}_4$.

The untreated muck, as shown in table 1, sorbed little phosphate. The muck that was treated to form quaternary ammonium compounds did sorb some phosphate, part of which was exchangeable when washed with $\text{N H}_2\text{SO}_4$. This experiment indicates that the anion capacity was appreciably increased by probable creation of more strongly basic amino compounds in the treated muck.

No anion release could be demonstrated after the amine-clay complexes were dried, as shown in table 3. It may be assumed that upon drying, the clay mineral crystals orient in a fashion that favors mechanical trapping of the organic molecules and their sorbed anions between the clay crystal layers, thus making them unavailable for exchange with $N H_2SO_4$.

It is interesting to note in table 3 that after the Wabash clay was dried, some of its phosphate that was in an exchangeable position was removed by washing with $N H_2SO_4$. The Jacob clay, on the other hand, after drying in the presence of the excess phosphate, fixed large amounts of phosphate which were unavailable

TABLE 2
Phosphate retained by Wabash clay (a black clay) and Jacob clay (a gray clay)

CLAY	ORGANIC CARBON	PHOSPHATE RETAINED		
		Before deamination		After deamination
		Washed with H_2O^*	Washed with $N H_2SO_4$	Washed with H_2O^*
	<i>per cent</i>	<i>me./100 gm.</i>	<i>me./100 gm.</i>	<i>me./100 gm.</i>
Wabash	7.88	22.3	8.9	21.5
Jacob	0.82	22.0	8.7	19.7

* Contained 1.6 me. of $H_2PO_4^-$ per liter, which was subtracted as a blank.

TABLE 3
Effect of drying on the retention of sorbed phosphate ions

CLAY	$H_2PO_4^-$ RETAINED		
	Washed with H_2O^*	Washed with $N H_2SO_4$ without drying	Washed with $N H_2SO_4$ after drying with excess $H_2PO_4^-$
	<i>me./100 gm.</i>	<i>me./100 gm.</i>	<i>me./100 gm.</i>
Diethylene triamine montmorillonite complex	24.5	5.5	24.7
Wabash	22.3	8.9	14.4
Jacob	22.0	8.7	32.0

* Contained 1.6 me. of $H_2PO_4^-$ per liter, which was subtracted as a blank.

for exchange. It may be that the organic matter of the Wabash clay keeps the clay particles labile and in a mechanical condition not quite so irreversible as that of the Jacob clay, thereby rendering the phosphate ions on the Wabash clay more susceptible to the action of solvents and replacing anions.

SUMMARY

Polyamine-clay complexes were found to have amino groups free for anion sorption and exchange. The sorption and exchange of anions by free amino groups were not important phenomena in the soil organic matter used in this investigation. This would indicate that polyamine compounds of sufficient basicity for anion sorption and exchange do not exist to any great extent in the soil.

Drying of the polyamine-clay complexes fixed phosphate in a nonexchangeable condition. Drying of soil clays also fixed phosphate. When dried, the soil clay high in organic matter fixed less phosphate than the clay low in organic matter.

REFERENCES

- (1) ADERIKHIN, P. G. 1946 Role of colloids in P_2O_5 absorption by soils. *Pedology* 9: 550-554.
- (2) BRADLEY, W. F. 1945 Molecular associations between montmorillonite and some polyfunctional organic liquids. *Jour. Amer. Chem. Soc.* 67: 975-981.
- (3) BRAY, R. H., AND DICKMAN, S. R. 1942 Adsorbed phosphates in soils and their relation to crop responses. *Soil Sci. Soc. Amer. Proc.* (1941) 6: 312-320.
- (4) COLEMAN, R. 1944 Phosphorus fixation by the coarse and fine fractions of kaolinitic and montmorillonitic clays. *Soil Sci.* 58: 71-77.
- (5) DEAN, L. A., AND RUBINS, E. J. 1947 Anion exchange in soils: I, II, III. *Soil Sci.* 63: 377-406.
- (6) DICKMAN, S. R., AND BRAY, R. H. 1941 Replacement of adsorbed phosphorus from kaolinite by fluoride. *Soil Sci.* 52: 263-273.
- (7) DOUGHTY, J. L. 1935 Phosphate fixation in soils, particularly as influenced by organic matter. *Soil Sci.* 40: 191-202.
- (8) ENSMINGER, L. E., AND GIESEKING, J. E. 1939 The adsorption of proteins by montmorillonitic clays. *Soil Sci.* 48: 467-473.
- (9) ENSMINGER, L. E. The relationship between water lost and PO_4 adsorbed on phosphating clay minerals and soil colloids. *Soil Sci. Soc. Amer. Proc.* (1948) 13. (In press.)
- (10) GIESEKING, J. E. 1939 The mechanism of cation exchange in the montmorillonite-beidellite-nonttronite type of clay minerals. *Soil Sci.* 47: 1-15.
- (11) GRIESSBACH, R. 1939 Über die Herstellung und Anwendung neuer Austauschadsorbentien, insbesondere auf Harzbasis. *Angew. Chem.* 52: 215-219.
- (12) HENDRICKS, S. B. 1940 Base exchange of the clay mineral montmorillonite for organic cations, and its dependence upon adsorption due to Van der Waal's forces. *Jour. Phys. Chem.* 45: 65-81.
- (13) KELLY, J. B., AND MIDGLEY, A. R. 1943 Phosphate fixation and exchange of phosphate and hydroxyl ions. *Soil Sci.* 55: 167-176.
- (14) KUNIN, R., AND MYERS, R. J. 1947 The anion exchange equilibria in an anion exchange resin. *Jour. Amer. Chem. Soc.* 69: 2874-2878.
- (15) KURTZ, L. T., DETURK, E. E., AND BRAY, R. H. 1946 Phosphate adsorption by Illinois soils. *Soil Sci.* 61: 111-124.
- (16) LOW, P. F., AND BLACK, C. A. 1948 Phosphate induced decomposition of kaolinite. *Soil Sci. Soc. Amer. Proc.* (1947) 12: 180-183.
- (17) MCAULIFFE, C. D., et al. 1948 Exchange reactions between phosphates and soils: Hydroxylic surfaces of soil minerals. *Soil Sci. Soc. Amer. Proc.* (1947) 12: 119-123.
- (18) MATTHEW, S. 1931 The laws of soil colloidal behavior: VI. *Soil Sci.* 32: 343-365.
- (19) MURPHY, H. 1937 The role of kaolinite in phosphate fixation. *Hilgardia* 12: 343-382.
- (20) NITZSCH, W. V., AND CZERATZKI, W. 1940 Die Beschaffenheit und Beeinflussbarkeit der Bodenkolloide und ihre Bedeutung für Krümelbildung und Krümeleigenschaften. *Bodenk. u. Pflanzenernähr.* 18: 1-40.
- (21) PERKINS, A. T. 1948 Kaolin and treated kaolins and their reactions. *Soil Sci.* 65: 185-191.
- (22) RAVIKOVITCH, S. 1934 Anion exchange: I, II. *Soil Sci.* 38: 219-239, 279-290.
- (23) SCARSETH, G. D. 1935 Mechanism of phosphate retention by natural alumino-silicate colloids. *Jour. Amer. Soc. Agron.* 27: 596-616.

- (24) SIELING, D. H. 1947 Role of kaolin in anion sorption and exchange. *Soil Sci. Soc. Amer. Proc.* (1946) 11: 161-170.
- (25) STOUT, P. R. 1940 Alterations in the crystal structure of clay minerals as a result of phosphate fixation. *Soil Sci. Soc. Amer. Proc.* (1939) 4: 177-182.
- (26) TOTTH, S. J. 1937 Anion adsorption by soil colloids in relation to changes in free iron oxides. *Soil Sci.* 44: 299-314.
- (27) WIKLANDER, L. 1946 Studies on ionic exchange with special reference to the conditions in soils. *Ann. Roy. Agr. Col. Sweden* 14: 87-92.

FIXATION OF AMMONIA BY LIGNIN¹

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Mattson and Koutler-Andersson² were able to fix nitrogen in certain organic compounds by oxidation with oxygen in aqueous ammonium hydroxide. This procedure yielded a product containing various amounts of nitrogen, depending upon the nature of the original material. The results obtained seemed to indicate that only substances containing at least two phenolic hydroxyls could fix much nitrogen. Part of the nitrogen fixed was resistant to the action of 72 per cent sulfuric acid and strong alkaline solutions.

If phenolic hydroxyl groups are responsible for the reaction, it should not be possible to fix nitrogen in a fully methylated compound. Unfortunately, however, compounds whose solubility in alkaline media depends upon the phenolic hydroxyl groups would not be ideal substances for use in testing the above statement. On the other hand, if an incompletely methylated sample of a substance bearing phenolic hydroxyls and aliphatic hydroxyls were subjected to the fixation reaction and nitrogen were fixed, would it be possible to increase the content of methoxyl? If the fixation reaction is somewhat specific and does not affect alcoholic hydroxyl groups, then methylation of the product should result in the production of a compound with a higher percentage content of methoxyl. One should not expect to introduce as much methoxyl as should be possible prior to the fixation process.

The object of this investigation was to determine whether hydroxyl groups are involved in the simultaneous oxidation and nitrogen fixation reaction as applied to lignin.

MATERIAL AND METHODS

Meadol³, a commercial lignin containing about 20.5 per cent methoxyl, was used. Four successive methylations using dimethyl sulfate and sodium hydroxide brought the methoxyl content to 34.1 per cent. Methoxyl and nitrogen were determined by the A. O. A. C. methods. Ammoniacal nitrogen was determined by the magnesium oxide method.

Oxidations were conducted by placing the lignin in a 500-ml. round-bottomed flask mounted on a shaker and closed by a two-hole rubber stopper containing two glass tubes. One tube extended nearly to the bottom of the flask and above the stopper about 6 inches; the other, a short right-angle bend extending just through the stopper, was connected to the supply of oxygen. The residual air was partly displaced by the passage of a stream of oxygen through the system

¹ Contribution No. 717 of the Massachusetts Agricultural Experiment Station.

² MATTSO, S., AND KOULTER-ANDERSON, E. The acid-base condition in vegetation, litter, and humus: VI. *Ann. Agr. Col. Sweden* 11: 107-134, 1943.

³ Kindly furnished by the Mead Corporation, Chillicothe, Ohio.

for a few minutes. Concentrated ammonium hydroxide was then poured down the long tube into the flask. The oxygen supply was then quickly connected. Several such flasks may be connected by means of T- and Y-shaped tubes. A steady oxygen pressure was maintained by regulating the depth to which a tube in the system was submerged in a bottle of water closed by a two-hole stopper. If additional pressure were applied, the extra gas would bubble through the water and escape into the air rather than force the ammoniacal solution out of the flasks. A head equivalent to the weight of a column of water about 100 by 4 mm. was maintained. Samples ranging in size from a few grams up to 50 gm. in concentrated ammonium hydroxide were used at a temperature of about 25° C. for about 150 hours. The connections were then broken, the ammonium hydroxide was removed at low temperature and reduced pressure, and the solid was recovered.

TABLE 1

Content of methoxyl and total nitrogen in Meadol before and after special treatments

SAMPLE	METHOXYL	TOTAL NITROGEN
	<i>per cent</i>	<i>per cent</i>
Untreated lignin.....	20.5	—
Methylated lignin.....	34.1	—
Methylated-oxidized lignin.....	33.0	0.36
Oxidized lignin.....	17.2	7.22
Oxidized-methylated lignin.....	29.2	2.60

RESULTS

The solution of lignin during this treatment became very dark. When complete methylation had preceded oxidation, lignin was relatively insoluble and underwent little if any change in color. The results are shown in table 1.

The ammoniacal nitrogen was relatively constant at about 33 per cent of the total nitrogen fixed. The data indicate that the nitrogen content of Meadol can be increased substantially by rather mild treatment and that methylation of Meadol essentially prevents fixation of nitrogen. Oxidation apparently did not alter the compound enough to prevent a considerable degree of methylation. It will also be noted that a relatively high percentage of the nitrogen added during oxidation remained bound even after the somewhat drastic methylation procedure.

These results are interpreted as indicating that the phenolic hydroxyl groups were destroyed during oxidation and that the increase in percentage of methoxyl effected by methylating the oxidized product was due to the presence of alcoholic, not phenolic, groups. The conclusion based on methylation studies would seem to support Mattson's contention that simultaneous oxidation and nitrogen fixation took place by way of the phenolic hydroxyl groups.

ABSORPTION OF P BY SOYBEANS AND SUDAN GRASS:

I. COMPARISON OF EFFECTS OF Mg, Ca, AND Na SALTS

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The influence of Mg upon the efficiency of utilization of P by plants is a subject of continuing interest. The problem of increasing the efficiency of utilization of P is highly important. Phosphorus has been called the master key of agriculture (4). Over the United States as a whole, P, more often than any other element, is the limiting factor in crop production and in nutritional deficiency diseases of grazing livestock.

There have been considerable speculation and research on the effects of Mg in enabling plants to utilize P. The theory, proposed by Loew (10), that one of the functions of Mg in plants is that of a carrier of P has been widely accepted (4, 9, 12, 17, 19). Since both Mg and P are usually high in oily seeds, the formation of oils is accompanied or preceded by the formation of lecithin, and Mg is found in greater amounts in plant cells when both lecithin and nucleoproteins are present than when one of these is absent, Loew theorized that Mg functions to facilitate the movement of P in the plant to the points where the P is synthesized into organic compounds.

Experimental data on the effects of Mg on the utilization of P are conflicting. Kellogg (9) concluded after a study on arid soils in North Dakota that a deficiency of Mg was the probable reason for lack of response to P fertilization on some soils. Truog and associates (17) found in a recent investigation that the concentration of P in garden peas was increased by increasing applications of high-Mg limestone and concluded that their data support the theory that Mg functions as a P-carrier. Hunter (7) found that when the proportions of Mg and Ca were varied reciprocally in a soil, increasing Mg, though greatly increasing the Mg content, had little effect upon the P content of alfalfa within the range in which Ca exceeded Mg and that significant increases in P uptake occurred only when the amount of available Mg in the soil approached closely, or became greater than, the amount of Ca. Bartholomew (1) added Mg to various phosphate fertilizers and found increases in P absorption in some cases and decreases or no effects in other cases. McGeorge (11) conducted extensive Neubauer tests on Arizona soils and concluded that the type of soil and kind of crop must be taken into consideration in drawing conclusions regarding the effects of Mg on absorption of P by plants. The data of Gericke and Polheim (6) indicated that the uptake of P from soil was in most cases not affected by treatment with Mg and Ca sulfates or carbonates, and that in some cases both sulfates caused a re-

¹The authors express their gratitude to Dr. Richard Bradfield for helpful suggestions during the course of these studies and to Mrs. Jeanne Darlington for making many of the analyses.

duction in P uptake. Fudge (5) did not detect any consistent effect of even very large applications of $MgCO_3$ upon the concentration of P in orange juice. Willis, Piland, and Gay (18), in studying the influence of Mg deficiency on P absorption by soybeans, found no significant effect of added Mg on P uptake from soils which were so Mg-deficient as to require fertilization with some Mg compound. Beeson, Lyon, and Barrantine (3), in investigating the absorption of nutrients by the tomato plant, found Mg and P in the leaves to be positively correlated but thought it questionable that Mg has a role in absorption of HPO_4^- by root cells.

The present study was undertaken to investigate further the influence of variations in the supply of Mg upon the absorption of P by plants and to compare the effects of Mg with those of Ca and Na when these elements were supplied in equivalent amounts and in combination with the same anions. Since in some studies Mg has been supplied as the carbonate, and the effects of Mg have to some extent been confused with those of pH changes, the carbonates of Ca and Na were included with $MgCO_3$ in the tests. Two investigations were conducted on soils and a third was made with sand-solution cultures.

MATERIALS AND METHODS

Experiments on soils

Two soils were used in the investigations. The soybean (var. Cayuga) was grown as the test plant in 2-gallon pots (with drains) of Ottawa fine sandy loam; sudan grass (var. Kansas Sweet), with an interplanting of ladino clover, was grown on 6 by 6-foot field plots of Mardin silt loam on the Mt. Pleasant farm of the Cornell University Agronomy Department, Ithaca, New York.

The 23 treatments listed in table 1 were applied to each soil; in each case there were four randomized replications, resulting in a total of 92 pots or field plots. Both soils received uniform applications of NH_4NO_3 and KNO_3 or KCl, in addition to the salts listed; applications equivalent to 50 pounds N and 50 pounds of K_2O per 2 million pounds of soil were thoroughly mixed with the Ottawa soil in pots; 50 pounds N, 100 pounds K_2O , and 1,500 pounds of limestone per acre were mixed lightly into the surface of the field plots of Mardin silt loam.

The phosphates of Mg and Ca were supplied on the basis of their P_2O_5 content, being applied at the rates of 150 pounds P_2O_5 per 2 million pounds to the Ottawa and 300 pounds per acre to the Mardin soil. The other salts were supplied at the rate of 60-pound equivalents per 2 million pounds (Ottawa) or per acre (Mardin), except for olivine and serpentine, which were applied at the rate of 120-pound equivalents (basis Mg, calculated from empirical formulas $MgFeSiO_4$ and $H_4Mg_3Si_2O_9$, for olivine and serpentine, respectively). Olivine and serpentine were ground to such fineness that about 95 per cent passed a 100-mesh screen. Except for the phosphates, all salts were applied in combination with two levels of P: (a) the natural level of the soil and (b) the level induced by the application of P_2O_5 , as $Ca(H_2PO_4)_2$, at the rates given above for the two soils. The modified Truog test (13) showed 3 and 60 pounds of available P per 2 million pounds of the Mardin and Ottawa soils, respectively. The exchangeable bases listed in table 1 are the summation of those initially present in the soil

AN 7 0.382

COMPARATIVE STUDY OF DECOMPOSITION RATES OF ORGANIC MATTER IN TEMPERATE AND TROPICAL REGIONS

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In comparison to the soils of the United States, the well-drained upland soils of the equatorial regions of Colombia, South America, are very rich in total nitrogen and organic matter. In particular, from localities with identical mean annual temperatures and precipitation the nitrogen and organic matter levels of Colombian soils are severalfold higher than those of United States soils (7).

The present paper shows that Central American as well as Colombian soils contain large amounts of organic matter. To facilitate quantitative comparisons with midlatitudes, organic matter levels of Californian soils also are reported. Furthermore, measurements of production and decomposition of organic matter in various climates are discussed.

NITROGEN AND ORGANIC MATTER LEVELS OF CENTRAL AMERICAN SOILS

In the fall of 1946 the senior author collected soil samples at various elevations in eastern Costa Rica.¹ The soils were analyzed at Berkeley, California, according to methods previously reported (7). All analytical results are recorded on an oven-dry basis.

In figure 1 are plotted the nitrogen-depth functions of seven well-drained Costa Rican upland soil profiles. They group themselves into the climatically warm Turrialba set and the relatively cool Juan Vías set. Though all profiles indicate high levels of soil nitrogen, those of the Juan Vías group display especially high values. The organic matter contents also are high, as may be judged from the high carbon-nitrogen ratios shown. The profile features of the Juan Vías soils are akin to the humic yellow-brown soils of Colombia (6).

In table 1 are presented nitrogen values, carbon-nitrogen ratios, pH values, and textures of 23 well-drained soils collected to a depth of 0 to 8 inches. The sites range in elevation from 300 to 4,200 feet. In all localities the mean annual rainfall is high, 70 to 150 inches. Mean annual temperature varies from about 76°F. in the hot lowlands to 65°F. on the cooler Central Plateau.

The nitrogen contents of these Costa Rican surface soils are very high. On the basis of mean annual temperature and precipitation, their nitrogen and organic matter contents are comparable to those of Colombian soils. Wheeting (13) has reported high nitrogen contents of Guatemalan soils also.

¹ The senior author is indebted to R. H. Allee, Director of the International Institute of Agricultural Sciences at Turrialba, Costa Rica, for arranging the author's sojourn at the Institute, and to N. C. Ives and S. Bonilla for assistance in collecting soil samples and conducting experiments.

SOIL NITROGEN LEVELS IN THE SIERRA NEVADA MOUNTAINS OF CALIFORNIA

In the region of Friant Dam, Shaver Lake, Huntington Lake, and Mt. Hilgard in California, a granitic batholith extends over a range of elevation from 500 feet to more than 13,000 feet. From an altitude of 2,000 feet to the timber-

TABLE 1
Analytical data of 23 well-drained Costa Rican soils
Depth 0-8 inches

NUMBER	N	C/N	pH*	TEXTURE	REMARKS
	per cent				
<i>Cairo, Elevation 300 feet</i>					
21	0.26	10.2	5.1	Sandy loam	Rubber plantation.
22	0.35	11.0	5.5	Sandy loam	Virgin forest, mineral soil only.
23	0.32	9.6	5.1	Sandy loam	Pasture.
Av.	0.31	10.3	5.2		
<i>Vicinity of Turrialba, Elevation 1,837 feet</i>					
1	0.33	12.7	6.3	Sandy loam	Young rubber plantation.
2	0.38	10.3	5.2	Loam	Coffee grove.
3	0.28	10.0	5.0	Silty clay loam	Sugar cane field.
4	0.61	11.3	6.6	Sandy loam	Coffee grove.
7	0.50	11.1	5.7	Sandy loam	Sugar cane field, 10 per cent slope.
8	0.46	12.3	5.8	Fine sandy loam	Best sugar cane field of Exp. Sta.
12	0.17	12.2	6.0	Loamy fine sand	Virgin forest, mineral soil only.
13	0.14	11.3	6.0	Loamy fine sand	Virgin forest, mineral soil only.
17	0.42	10.7	5.6	Loam	Abandoned coffee grove
18	0.38	13.9	6.1	Sandy loam	Plowed field
24	0.25	12.8	4.9	Loam	Field crops, 30 per cent slope.
25	0.37	14.3	5.0	Loam	Field crops, 15 per cent slope.
Av.	0.36±	11.9±	5.7		
	0.04	0.39			
<i>Vicinity of Juan Viñas, Elevation about 4,200 feet</i>					
9	1.23	13.4	5.6	Organic loam	Sugar cane, 30 per cent slope.
10	0.81	17.4	5.5	Organic sandy loam	Pasture, 30 per cent slope.
11	0.91	14.5	5.3	Organic loamy sand	Pasture, 50 per cent slope.
14	0.99	14.8	5.3	Organic loamy sand	Pasture, 10 per cent slope.
15	0.92	13.2	6.0	Organic sandy loam	Sugar cane, 20 per cent slope.
16	1.05	18.1	5.4	Organic sandy loam	Sugar cane, level spot on knoll.
Av.	0.99±	15.2±	5.5		
	0.06	0.84			

* 1:2 soil-water ratio.

line at about 10,000 feet, the soils belong to the "podzolized yellow-red soils," having well-defined light gray A₂ horizons and yellow or reddish B horizons.

In this mountain range were duplicated the profile studies and the measurements of production and decomposition of organic matter carried out simultaneously in Costa Rica and Colombia. In figure 2 is portrayed the variation of the nitrogen content of the soil (0-8 inches, exclusive of forest floor) with eleva-

tion and type of vegetation. All analyses pertain to the fine earth fraction (<2 mm.) of the soil. No corrections for stone contents were made. For comparison, the corresponding relationships between soil nitrogen and elevation in Colombia and Costa Rica also are included in the graph.

The great contrasts in the nitrogen contents of the selected equatorial (Colombia and Costa Rica) and midlatitude soils are clearly brought out. The authors believe that the soil samples collected are representative of large areas.

MEASUREMENTS OF PRODUCTION OF ORGANIC MATTER BY VEGETATION

There is in the Americas a deplorable lack of data on the production of organic matter by forest vegetation. This deficiency is especially noticeable in tropical regions. Whereas it is relatively easy, because of the shedding of leaves in October and November, to collect freshly fallen leaf litter of deciduous trees in

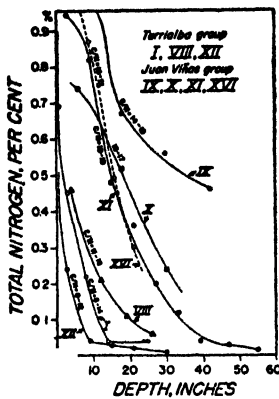


FIG. 1. NITROGEN-DEPTH FUNCTIONS OF SOILS FROM COSTA RICA

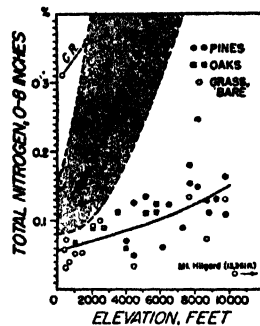


FIG. 2. RELATIONSHIP BETWEEN NITROGEN CONTENT OF SOIL (0-8 INCHES) AND ELEVATION IN CALIFORNIA

Range of Colombian soils and Costa Rican (C.R.) averages also are indicated.

North America, collection of litter in equatorial regions must be extended over an entire year.²

Leaf collectors were placed in virgin forests of Colombia (2) and California. The collectors consisted of square wooden frames 4 to 6 inches high. To the bottom of the frame was fastened a metal mosquito screen which rested directly on the soil. The Colombian collectors had an inside area of 1 square meter; the California ones measured half a square meter. The frames were placed 6 feet from a tree trunk. At frequent intervals the leaves, needles, fruits, twigs, and all other plant materials that fell into the collectors were removed and weighed. This material is here designated as *litter*. The forest floor below the collectors was also sampled.

The seasonal variation of litter production in tropical forests is depicted in figure 3. The two Chinchiná samplers were several hundred feet apart, one being

² The senior author was fortunate in obtaining the cooperation of L. O. Souffront in Chinchiná and of V. M. Patiño in Cali in measuring leaf fall in tropical rain forests during 1947.

below a large mestizo tree (*Guarica Gigantea*), the other under medium-sized broad-leaved trees and shrubs.

In table 4 are listed the annual values of litter production (A) on an over-dry basis (105°C.). The California data were collected during 1947-48. It is important to note that the annual productions of litter in the tropical locations exceed those in California. On an acre basis the tropical forests dropped in a year 8,000 to 11,000 pounds of leaves and twigs, whereas the Sierra trees produced only 800 to 3,000 pounds.

DECOMPOSITION VELOCITIES OF ALFALFA IN VARIOUS CLIMATES

Quantitative information on decomposition velocities of organic matter in various climates was obtained (table 2) by putting into natural soils metal cans containing dried alfalfa leaves (3.5 per cent nitrogen).

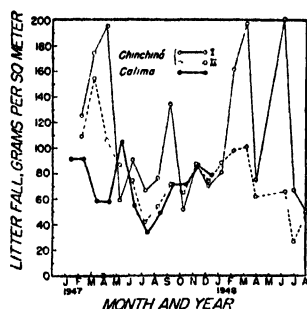


FIG. 3. VARIATION OF MONTHLY LITTER FALL IN TROPICAL RAINFORESTS

Multiplying grams per square meter by 8.92 gives pounds per acre. Summations are given in table 4.

The metal containers were constructed from two types of cans obtained from the Continental Can Co. They were type L. Plate, No. 211-301 (7 cm. height, 6.7 cm. diameter) and No. 211-400 (10 cm. height, 6.7 cm. diameter). The cans were stripped of their top and bottom parts. The short cylinder was then soldered on the long one, the two being separated by a metal screen. The bottom cylinder was left empty; the top cylinder was filled with the following layers of material (see figure 4): glass wool, alfalfa leaves (10 or 15 gm.), filter paper, glass wool. The top cylinder was capped with a galvanized wire net consisting of material from commercial pot cleaners.

These receptacles were placed vertically in the soil, so that only the top half inch emerged above the surface. Alfalfa was inoculated with soil suspension.

In every locality eight cans were placed within an area of 1 square meter. At 3-month intervals two cans were removed, and their contents were dried and sent by air mail to Berkeley where they were weighed and analyzed. One hundred and twelve cans were placed in Costa Rica (in 1946) and Colombia (in 1946-47) and more than 600 in various parts of California (1946-1948). Because of human and animal interferences the mortality rate of the cans was fairly high, especially in the tropics, where even sites were lost as a result of rapidly growing vegetation.

TABLE 2
Localities, climate, and names of cooperators of alfalfa decomposition studies
 Figures in parantheses denote estimated values

NUMBER	LOCALITY	ELEVATION feet	ANNUAL CLIMATE OR CLIMATE DURING EXPERIMENT			DATE OF SETTING OUT CANS	* COOPERATORS
			Temperature °C.	°F.	Precipitation mm. inches		
1*	Costa Rica (N. C. Ives, Turrialba, in charge). Ten grams of alfalfa exposed.	250	24.4	75.9	3.007	Oct. 2, 1946	H. Echeverri
2	Diamantes, lawn	820	24.4	75.9	3.007	Oct. 2, 1946	H. Echeverri
3	Diamantes, under tree	250	24.4	75.9	3.007	Oct. 3, 1946	H. Echeverri
4	Cairo, bare soil	91	24.2	75.5	3.747	Oct. 4, 1946	G. Bonilla
5	Turrialba, jungle	500	(22.8)	(73)	(1,870)	Oct. 4, 1946	G. Bonilla
6	Turrialba, rubber plantation	500	(22.8)	(73)	(1,870)	Oct. 4, 1946	A. Lizano
7	Turrialba, Hulera (lawn)	560	22.5	72.5	1,872	Oct. 6, 1946	G. Bonilla, and
8	Juan Viñas, bare soil	1,280	18.4	65.1	3,581	Oct. 5, 1946	E. A. Strauman
	Colombia (L. O. Souffront, Chinchiná, in charge). Fifteen grams of alfalfa exposed.	1,311	(18.3)	(65)	(3,581)	Oct. 5, 1946	
9	Calima, lawn	30	26.6	79.9	9,123	Dec. 15, 1946	V. M. Patiño, C. Pontón Rangel
10	Palmira, lawn	1,066	24.0	75.2	956	Dec. 18, 1946	G. Ramirez
11	Villavicencio, lawn	498	26.3	79.3	4,033	Jan. 25, 1947	Marston Bates
12	Chinchiná, lawn	1,433	22.0	71.6	2,769	Dec. 9, 1946	L. O. Souffront
13	Chinchiná, jungle	1,630	(21)	(70)	(2,800)	Dec. 9, 1946	L. O. Souffront
14	Bogotá, lawn	2,640	(14.5)	(58.1)	(976)	Feb. 4, 1947	J. Ancizar-Sordo

* Samples 1, 2, 3, 6, 7, 9, 10, 11, 12 were placed within a few feet of rain gauges and thermographs.

Results from Colombia

Figure 5 shows the accumulative losses of alfalfa (percentage of oven-dry weight) in relation to time of exposure. A high initial rate of loss is followed by lower rates. In the perhumid tropical area of Calima nearly 100 per cent of the alfalfa disappeared in 1 year. Chinchiná, having a subtropical humid climate, also provided large losses of organic matter. Palmira and Bogatá have lower rates of loss. Presumably the relatively low annual rainfall, 38 inches for both localities, mainly controlled the rates of decomposition.

For the sake of comparison, the decay curve of alfalfa at 25°C. obtained in a laboratory thermostat at optimum moisture conditions also is plotted in figure 5. It lies below the Calima (26°C.) and Chinchiná (24°C.) curves. Since only

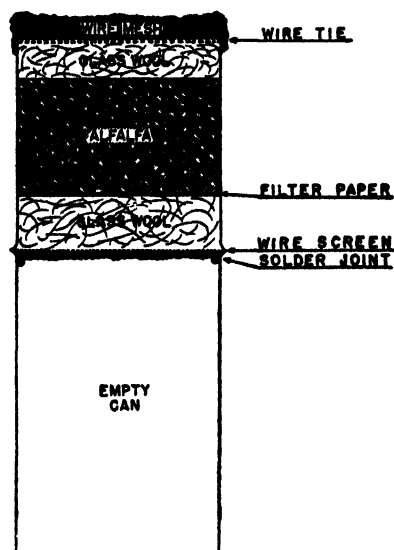


FIG. 4. TYPE OF CAN USED FOR STUDIES ON DECOMPOSITION OF ALFALFA IN SOILS

gaseous losses are measured in the laboratory experiments, the differences among the curves must be attributed to losses caused by leaching. In both field and laboratory the nitrogen losses were nearly proportional to the weight changes.

Results from Costa Rica

To portray more accurately the diversified pattern of the eight Costa Rican decay curves, the scale on the vertical axis of figure 6 is enlarged. All alfalfa samples exhibit heavy losses of material, especially those at the Goodyear Rubber Experiment Station in hot and humid Cairo. Even at "cool" Juan Viñas the losses are high, possibly as the result of heavy leaching. In all instances the initial losses exceed the initial rates of decay of the 25°C. laboratory set.

Results from Sierra Nevada Mountains, California

In contrast to the humid tropical and subtropical climates, the rates of decomposition of alfalfa in the Sierra Nevada Mountains are much lower (fig. 7). The results of many of field experiments suggest the following explanations:

a) At low elevations (Madera) decomposition occurs mainly during the rainy season, normally from September to March. The high summer temperatures are ineffective because of lack of moisture.

b) At high elevations decomposition is restricted to early fall and late spring. The winter months are too cold and the summer months are too dry to influence the rate of decay.

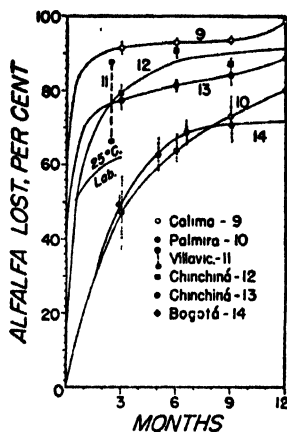


FIG. 5.

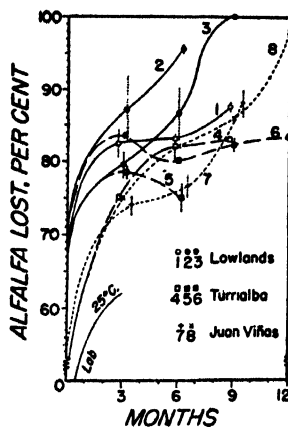


FIG. 6.

FIG. 5. ACCUMULATIVE SEASONAL DECOMPOSITION AND LOSSES OF ALFALFA IN THE FIELD IN COLOMBIA

The dotted vertical lines show the variations between duplicate cans. From Villavicencio only one collection was available.

FIG. 6. ACCUMULATIVE SEASONAL DECOMPOSITION AND LOSSES OF ALFALFA IN THE FIELD IN COSTA RICA

Note the change in ordinates in comparison with figure 5. The dotted vertical lines indicate the variation between duplicate cans. Absence of these lines denotes variability too small to be plotted.

The dependency of the annual losses of alfalfa on elevation, annual precipitation, and annual temperature is shown in figure 8. The seemingly erratic decomposition curve faithfully records the variation in annual precipitation and temperature with elevation. From 300 to 3,000 feet elevation, decomposition rises because rainfall increases. Annual temperatures vary but little. Between 3,000 and 7,000 feet, precipitation remains nearly constant, whereas temperature falls notably. Accordingly, the rate of decomposition is reduced from 74 per cent to 59 per cent. In the range of 7,000 to 9,000 feet, precipitation rises sharply, causing an acceleration in decay, in spite of a lowering of temperature. Between 9,000 and 10,000 feet, precipitation remains constant, temperature decreases, and the rate of decomposition declines.

Summary of decomposition rates of alfalfa in situ

To summarize conveniently the decomposition studies, the residues, that is, the weight percentages of alfalfa left in the cans at the end of one year's exposure, are plotted in a temperature-precipitation diagram (fig. 9). The height of each

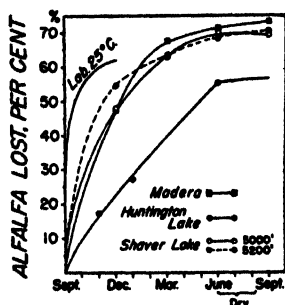


FIG. 7.

FIG. 7. ACCUMULATIVE SEASONAL DECOMPOSITION AND LOSSES OF ALFALFA IN THE FIELD IN THE SIERRA NEVADA MOUNTAINS, CALIFORNIA

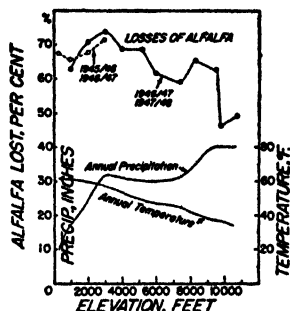


FIG. 8.

FIG. 8. ANNUAL LOSSES OF ALFALFA IN THE SIERRA NEVADA MOUNTAINS IN RELATION TO ELEVATION, ANNUAL TEMPERATURE, AND PRECIPITATION

At higher elevations the precipitation values were obtained from rain gauges and snow survey data of the California Edison Company.

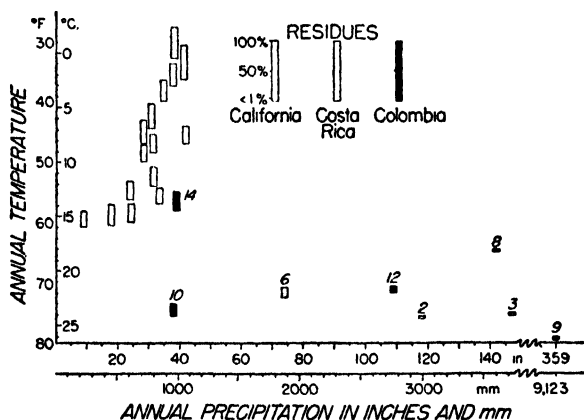


FIG. 9. FRACTION OF ALFALFA LEFT IN CANS (RESIDUES) AFTER 1 YEAR'S EXPOSURE

Length of bar indicates residue in percentage of original amount. Coordinates correspond to the climate of the sites. Numbers denote site number (table 2).

bar denotes the residue of alfalfa. The locus of the center of the base of each bar indicates the annual temperature and precipitation of the site. Whereas the tropical sets represent 1-year studies (1946-47), the California values are averages of two experiments (1946-47 and 1947-48).

In its broader aspects the diagram reflects the climatically controlled organic

matter content of soils. In accordance with North American and Colombian climate functions, the residues are small at high temperatures and high moistures and large at low temperatures. Clearly, in the hot, humid tropics decomposition of alfalfa is very marked. Abundant rainfall seems to be especially effective in reducing the amount of alfalfa left in the cans.

The alfalfa studies permit an examination of Corbet's assertion (1) that insola-

TABLE 3
Role of type of plant cover (microclimate) on the losses of alfalfa

LOCALITY	TYPE OF PLANT COVER	AMOUNT OF ALFALFA LOST	
		Period	Amount
		months	per cent
Chinchiná, Colombia	Jungle	9	85
	Lawn (cut)	9	90
Diamantes, Costa Rica	Large tree and ferns	6	95
	Adjacent lawn (cut)	6	83
Cairo, Costa Rica	Bare soil	6	87
Turrialba, Costa Rica	Jungle	6	82
	Young rubber plantation	6	75
	Lawn (cut)	6	80
Berkeley, California	Canary pine (dense stand)	12	71
	Adjacent grass	12	70
Whittacker Forest, California	White fir, very shady	13	74
	Adjacent, sunny opening	13	72
Mt. Givens, California	Western white pine (dense stand)	12	43
	Adjacent bare ground, open	12	43
O'Neils, California	Under chaparral	12	73
	Adjacent grass, sunny	12	69

tion is the prime factor which determines the rate of loss of organic matter in tropical regions. To the contrary, according to the comparisons listed in table 3, there is neither a marked nor a consistent difference between losses of alfalfa in jungle, under isolated trees, on lawns frequently cut, or in bare soil. If such differences do exist, they are of secondary importance in comparison to the effects produced by temperature and precipitation of the macroclimate.

DECOMPOSITION VELOCITIES OF FOREST FLOORS

It appears possible to measure *in situ* the rate of decomposition of forest floors, provided certain conditions are fulfilled.^a

^a The ideas are not new in principle (3, 5, 9, 10, 11) but they are in their specific applications. Rode (12) mentions Kostychev's work in 1885.

In a deciduous climax forest which has reached a quasi-equilibrium stage, the forest floor, that is, all organic material lying on the mineral soil, exhibits a rhythmical variation. The amount of forest floor is lowest (F_E) in autumn, just prior to the annual fall of leaves. It is highest (\mathfrak{F}_E) immediately after the drop of leaves. In an equilibrium forest the annual rate of addition of organic material is equal to the annual rate of loss.

The *rate of addition* is given by the average annual fall of leaves and twigs and other parts of the tree. For a large area within a climax forest it is presumably a constant, say A pounds of organic matter per acre per year.

The *rate of loss* is given by the average amount of forest floor that disappears during 1 year. The losses consist of evolution of gas and of migration of soluble and dispersed humus substances into the mineral soil. In a stabilized forest the average rate of loss also is a constant, say, L pounds of organic matter per acre per year.

A schematic illustration of the rhythmic variation is given in figure 10. To simplify quantitative treatment, it is postulated that the annual fall of leaves takes place very rapidly, in the relatively short time interval dt . Accordingly, in figure 10, the maximum (\mathfrak{F}_E) and the minimum (F_E) values of the equilibrium forest floor have practically the same x -coordinates, t , $t + 1$, $t + 2$, etc.

During the 1-year time interval from t to $(t + 1)$ a certain fraction (k') of the forest floor decomposes. In an annual equilibrium system this loss is balanced by the addition A . We may write

$$\begin{aligned} A &= k' \mathfrak{F}_E, \text{ or} \\ A &= k'(F_E + A) \end{aligned} \quad (1)$$

We may also write, more precisely,

$$\begin{aligned} A_n &= k'_g F_E; \text{ since } A_n = A - k'_a A, \\ A &= k'_g F_E + k'_a A \end{aligned}$$

we obtain

The loss constants k' , k'_g , k'_a , are functions of the soil-forming factors;⁴ in other words:

$$k' = \frac{A}{\mathfrak{F}_E} = \frac{A}{F_E + A} = f(cl, o, r, p, t) \quad (2)$$

This constant k' is an average for the various layers of the forest floor.

In a tropical rainforest, leaves drop continuously (fig. 3). Equilibrium may be visualized as being maintained at every instant. During the short time interval dt the following equality exists:

$$\begin{aligned} A dt &= k(F_E + A) dt, \text{ or} \\ A &= k(F_E + A) \end{aligned}$$

which is identical with equation (1).

The magnitude of k' may be calculated for any given locality, provided near-equilibrium conditions of litter fall and forest floor obtain. Experimental values

⁴ Unfortunately the authors failed to determine k'_a in the field. All calculations in this paper are based on k' only.

of k' for volatile matter (loss of ignition) are given in table 4. They were calculated from 1-year collections of litter fall and from the forest floor underlying the collectors. Near-equilibrium conditions were assumed to exist. In the per-humid tropical rainforest of Calima the annual loss constant reaches a high value of $\frac{730}{730 + 432} = 63$ per cent. In the moist subtropical region of Chinchiná the value of k' is 39 per cent. In contrast, the California values are much lower, varying from 6 to 12 per cent for oaks and 1 to 3 per cent for pines. The variations

TABLE 4

Litter fall, forest floors, and their rates of loss (k')

To convert gm./sq.m. to lb./A. multiply by 8.92

Sequence of localities arranged according to decreasing k' values.

NUMBER	LOCALITY	TYPE OF VEGETATION	LITTER FALL (A)		FOREST FLOOR (F E)		k' VOLA- TILE MAT- TER*	TIME
			Total	Vola- tile mat- ter*	Total	Volatile matter*		
			gm./ sq.m.	gm./ sq.m.	gm./ sq.m.	gm./ sq.m.	per cent	years
<i>Colombia</i>								
76	Calima	Broad-leaved rain forest	852	730	504	432	62.8	8
—	Chinchiná I	Large mestizo tree	1,205	1,115	—	—	—	—
78	Chinchiná II	Broad-leaved forest	1,011	985	1,648	1,455	39.1	6
<i>California</i>								
19	Elevation 4,000 feet	Black oak† (50-100 years)	128	122	—	924	11.7	24
41	" 6,000 feet	" " (75-100 years)	92	88	—	724	10.8	26
23	" 5,000 feet	" " "	155	149	4,381	2,517	5.59	52
18	" 4,000 feet	Ponderosa pine‡ (150 years)	160	143	—	4,741	2.93	101
22	" 5,000 feet	" " "	314	305	18,837	12,635	2.36	126
24	" 7,300 feet	" " "	249	246	—	12,351	1.95	152
43	" 6,000 feet	" " "	133	129	—	8,705	1.46	203
36, 37	" 9,800 feet	Lodgepole pine§ (200 years)	116	101	—	11,081	0.90	332
—	" 5,000 feet	Mixed conifers (50 years)	454	435	—	14,453	2.92	102

* Loss on ignition.

† *Quercus kelloggii*.

‡ *Pinus ponderosa*.

§ *Pinus contorta*.

of k' within the oak and pine groups are conditioned by elevation, local climate, density of stand, and other variables. By selection of trees free of fire scars, it was hoped to minimize possible disturbances of forest floors by fires.

TIME FUNCTIONS OF ACCUMULATION OF FOREST FLOORS

Foresters (4, 8) have calculated the time necessary to reach equilibrium of forest floor accumulation by dividing the amount of annual leaf fall into the amount of forest floor. An additional mode of computation is proposed and its limitations are stressed here.

Suppose we enter a climax forest that has reached a quasi-equilibrium state. Let us select a spot or area that represents average conditions, and let us there remove the forest floor until the mineral soil is exposed. Now, we wish to inves-

tigate, over a long period, the accumulation of litter and the formation of the forest floor.

We may consider the special case of an oak tree (table 4) which sheds annually 1,000 pounds of leaves per acre. A decomposition constant of 10 per cent is assumed to obtain throughout the life of the forest floor. The floor oscillates as suggested in figure 10. On the basis of these special conditions and simplifications, the build-up of the forest floor is depicted in figure 11. By a zigzag path the floor eventually approaches the steady state shown in figure 10. The inset in figure 11 displays the annual rate of increase.

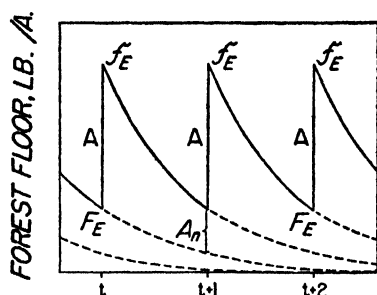


FIG. 10.

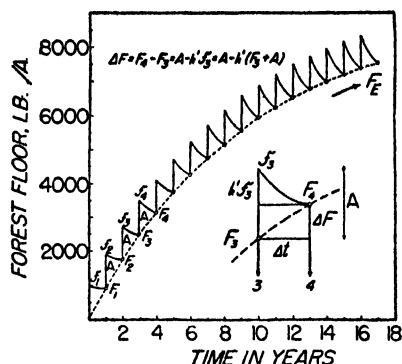


FIG. 11.

FIG. 10. SCHEMATIC ILLUSTRATION OF RHYTHMIC VARIATION OF FOREST FLOOR IN A DECIDUOUS FOREST AT EQUILIBRIUM

FIG. 11. BUILDING UP OF A FOREST FLOOR UNDER CONDITIONS OF INVARIANT k

We may develop the following simple geometrical series:

$$\begin{aligned} \mathfrak{F}_1 &= A \\ F_1 &= \mathfrak{F}_1(1-k') = A(1-k') \\ \mathfrak{F}_2 &= F_1 + A = A + A(1-k') \\ F_2 &= \mathfrak{F}_2(1-k') = A(1-k') + A(1-k')^2 \\ F(t) &= \frac{A(1-k')[1-(1-k')^t]}{k'} = F_\infty[1-(1-k')^t] \end{aligned} \quad (3)$$

This equation describes the sequence of the F_1, F_2, F_3, \dots values indicated in figure 11 by small circles.

In regions such as the humid tropics where the litter fall occurs through the year (fig. 3), the F values form a nearly continuous curve, as illustrated by the broken line in figure 11. For such conditions the increase in the forest floor during the time dt is given by

$$dF = A dt - k(F + A) dt = [A(1-k) - kF]dt.$$

Upon integration

$$\begin{aligned} F &= \frac{A(1-k)}{k} (1 - e^{-kt}) = F_\infty(1 - e^{-kt}), \\ k &= -\ln(1 - k') \end{aligned} \quad (4)$$

Figure 12 illustrates equation (4) for tropical and Sierran profiles.

Another way of expressing the trend of the broken line in figure 11 is as follows: The rate with which the forest floor reaches equilibrium is proportional to the difference between the amount of forest floor at any time and its equilibrium value, or, in the form of a differential equation

$$\frac{dF}{dt} = k(F_E - F).$$

Integration of this equation also yields equation (4). Again it is postulated that k remains constant throughout the life of the forest floor.

According to equation (4) final equilibrium will be reached only after a very

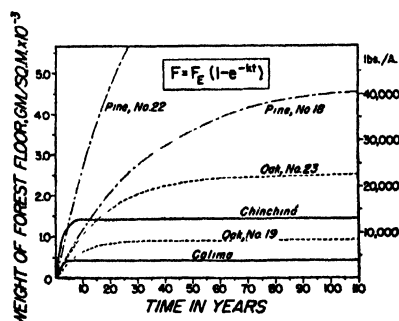


FIG. 12. TIME FUNCTIONS OF FORMATION OF FOREST FLOORS (VOLATILE MATTER)

long time. For practical purposes we may calculate the time necessary to reach, say, 95 per cent of the equilibrium value, according to the equation

$$t = - \frac{\ln \left(\frac{F_E - F}{F_E} \right)}{k} = - \frac{\ln \left(\frac{100 - 95}{100} \right)}{k} = \frac{3.0}{k} \quad (5)$$

These time periods are given in table 4. Assuming the validity of equation (5), one would conclude that in the two tropical soils near-equilibrium of the forest floor is reached in a few years. In the Sierra Nevada Mountains oak forest floors would be established in a few decades. Pine forest floors would require one or two centuries to approach a steady state.

DISCUSSION

The loss constants of forest floors determined *in situ* corroborate the annual loss rates of alfalfa. Since alfalfa decomposes more readily than palm leaves, oak leaves, or pine needles, the absolute values of the loss rates for alfalfa are high, but for both sets of observations the values are much higher in the tropics than in California.

Although these studies yield conclusive information on the effect of climate on the rate of decomposition of organic residues, they do not provide a direct clue as to the cause of the high organic matter levels in tropical soils. In fact,

the alfalfa and the forest floor studies would lead one to expect low contents of carbon and nitrogen in tropical soils.

An attempt to bring into harmony the two conflicting observations—high content of soil organic matter and high rates of decomposition of leaf materials—will be made in a forthcoming paper.

SUMMARY

Many Colombian as well as Costa Rican soils are very rich in nitrogen and organic matter, especially in comparison with Californian soils found in the Sierra Nevada Mountains.

Annual production of organic matter in the form of leaves and twigs is much greater in tropical forests (7,600–10,700 pounds per acre) than in Sierran forests (820–2,800 pounds per acre).

Alfalfa leaves placed in natural soils decompose rapidly in tropical soils and slowly in temperate soils.

Calculations of decomposition rates of forest floors in Colombia and California corroborate the results of the alfalfa studies.

The time required to reach near-equilibrium accumulation of forest floors is calculated to be less than a decade in tropical forests, 30 to 60 years under California oak, and 100 to 200 years under Ponderosa pine.

REFERENCES

- (1) CORBET, A. S. 1935 *Biological Processes in Tropical Soils*. W. Heffer and Sons, Cambridge.
- (2) CUATRECASAS, J. 1946 *Vistazo a la vegetación natural del Bajo Calima*. Presentación de Calima; Departamento del Valle del Cauca, Secretaría de Agricultura y Fomento, Cali, Colombia.
- (3) HENIN, S., AND DUPUIS, M. 1945 *Essai de bilan de la matière organique du sol*. *Ann. Agron.* 15: 17–29.
- (4) HEYWARD, F., AND BARNETTE, R. M. 1936 *Field characteristics and partial chemical analysis of the humus layers of long leaf pine forest soils*. *Fla. Agr. Exp. Sta. Bul.* 302.
- (5) JENNY, H. 1941 *Factors of Soil Formation*. New York.
- (6) JENNY, H. 1948 *Great soil groups in the equatorial regions of Colombia*, *S. A. Soil Sci.* 66: 5–28.
- (7) JENNY, H., BINGHAM, F., AND PADILLA-SARAVIA, B. 1948 *Nitrogen and organic matter contents of equatorial soils of Colombia*, *S. A. Soil Sci.* 66: 173–186.
- (8) KITTREDGE, J. 1948 *Forest Influences*. New York.
- (9) LEEFER, G. W. 1938 *Organic matter of soil as determined by climate*. *Jour. Aust. Inst. Agr. Sci.* 4: 145–147.
- (10) NIKIFOROFF, C. C. 1937 *Some general aspects of the chernozem formation*. *Soil Sci. Soc. Amer. Proc.* (1936) 1: 333–342.
- (11) NIKIFOROFF, C. C. 1942 *Fundamental formula of soil formation*. *Amer. Jour. Sci.* 240: 847–866.
- (12) RODE, A. 1945 *Review of Nikiforoff's fundamental formula of soil formation*. (In Russian.) *Pochvoved.* 1945: 222–225.
- (13) WHEETING, L. C. 1939 *Some observations on the soils of the Pacific slope of Guatemala*. *Proc. Sixth Pacific Sci. Conf.* 4: 885–889.

COMPOSITION OF CERTAIN SOIL ORGANIC MATTER FRACTIONS¹

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Although soil organic matter is formed from a variety of materials and under widely different conditions, the final product is remarkably uniform. This is often taken as evidence either that different substances are converted to the same material or that one or two plant constituents produce most of the organic matter, the others being decomposed. Possibly a combination of these processes takes place. When plant materials are decomposed, the carbohydrate and nitrogenous materials disappear much more rapidly than the lignin. Thus the latter tends to accumulate and is said to be one of the main constituents of humus.

Hebert and Deherain (22, p. 186) put forward the theory that humus is a mixture of lignin derived from plant material and of protein formed by microbial synthesis. Waksman and Iyer (21) prepared lignin-protein complexes by using alkali lignin from rye straw, cypress, or chestnut wood, and casein, gliadin, or egg albumin as the protein. Formation of these complexes increased the base-exchange capacity of the materials and the resistance of the protein to microbial attack. Waksman reported that union of the NH_2 group of the protein with a ketonic or aldehydic CO group was fairly probable and would produce a stable complex.

Mattson and Koutler-Andersson (14) concluded that the lignonitrogenous complex is formed by the interaction between lignin and ammonia and possibly also between lignin and decomposition products of proteins such as aromatic amines. Lignin thus would conserve nitrogen by tying up its soluble compounds in stable complexes. Amidophenols might be formed, and these compounds could be oxidized easily to form quinoneimids, which might then condense to form dark colored material.

Great advances have been made in the chemistry of lignin in the last 10 or 15 years, but the studies have been made largely on the lignin of wood and therefore not on the type of lignin that is added to the soil in plant and animal residues. Lignin isolated from these latter sources is invariably contaminated with nitrogenous materials and is usually lower in methoxyl than wood lignin. The literature of the chemistry of lignin especially as it pertains to soils has been reviewed by Gottlieb and Hendricks (8).

The ultraviolet absorption spectra of lignin and of compounds related to it have been extensively studied (7, 16, 17, 18). These investigations have indicated that lignin is aromatic in nature and that it has a characteristic absorption spectrum with a band in the region of 2,800 Å. which is said to be the result of "freedom of the position meta to the point of attachment of the side chain" (16). There is a second maximum at about 2,300 Å. which is said to be due to "some unexplained characteristic of the aromatic nucleus" (16).

Morrow and Gortner (15) found the Van Slyke nitrogen distribution of a number of soil types to be very uniform. Hobson and Page (10) found that a large part of the nitrogen of humic acid was amino nitrogen, and therefore they concluded that the major part of the

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soil nitrogen was in the form of protein derivatives although little could be liberated by the proteoclastic enzymes.

More recently Kojima (11) reported that 50 per cent of the nitrogen of a muck soil might be protein in nature on the basis of amino and amide nitrogen determinations. A considerable part of the amino nitrogen could be accounted for as amino acids (12).

In spite of the evidence noted, the lignin-protein theory of soil organic matter has never been proved and some investigators do not agree with it (6, 14). Soil nitrogen compounds have usually failed to give the common protein tests; on acid hydrolysis, the humin nitrogen has been high, and enzymic digestion usually has failed to yield significant amounts of soluble nitrogen. The soil nitrogen compounds may be much more stable than proteins, and it is hard to see why microbial proteins should be so much more resistant to decomposition than other protein material. Forsyth found that nitrogen remained attached to humic acids during methylation, acetylation, and esterification. That a linkage of protein to humic acid could be stable to these treatments seemed very improbable. This nitrogen must have been part of the molecular structure (6).

The present work was undertaken to study the nature of the organic material isolated during separation and fractionation of soil colloids. In a previous paper (1) a method was described for separating the colloidal matter of the soil into groups and for isolating various humate fractions. Results obtained with a group of Canadian soils over 3 years (2) indicated a relationship between crop yields and the amounts of group 1 colloids in the soils and tended to support the contention of Tyulin (19) that the humate fractions of this group are important to soil fertility. It seemed, therefore, that an investigation into the chemistry of these humate fractions might supply useful information, particularly in view of the fact that they were extracted with weak reagents and thus should not be greatly altered in the process of isolation. The objects of the investigation were twofold: first, to determine whether these humate fractions appeared to be of a lignoprotein nature; and second, to compare the chemical composition of the first and second humate fractions to see whether these materials were different chemically or different merely in the manner in which they were adsorbed on the soil minerals in such a way as to affect the method necessary to extract them.

MATERIALS AND METHODS

The soil selected for this investigation was from the black soil zone of western Canada. Analysis showed that it contained 6.2 per cent carbon and 0.67 per cent nitrogen.

Separation of humate fractions

A total of 450 gm. of soil was saturated with sodium by leaching with 25 per cent NaCl solution until there was no test for calcium. The excess chloride was then removed with ethanol. The Na-saturated soil was dispersed uniformly in water by stirring, and the suspended material was removed after 10 minutes. This process was repeated several times until the supernatant liquid appeared to be free of organic matter.

The combined soil suspensions were thoroughly mixed and the mineral matter precipitated by addition of KCl. The suspension was then centrifuged, the clear

liquid (which contained considerable amounts of organic matter in solution) was acidified, and a precipitate of organic matter, which will be called the "first humate fraction," was obtained by filtering or centrifuging. The KCl precipitate was washed several times in the centrifuge tubes with 0.01 *N* HCl, then dispersed in 12 liters of 0.01 *N* NaOH. The mineral matter was precipitated with KCl and filtered off. The filtrate was treated with acid, and the organic matter, which will be referred to as the "second humate fraction," was precipitated.

Both humate fractions were dried at 50°C. in a vacuum oven and ground to pass a 200-mesh screen.

Isolation of "lignin"

"Lignin" was separated from the two humate fractions by a method similar to that described by Manning and DeLong (13). In the final washing the residue, theoretically pure lignin, started to dissolve after the acid was washed out, and it was necessary to complete the washing with weak acid solution (a few drops of HCl per liter).

Acid hydrolysis

Two-gram samples of each humate fraction were refluxed with 6 *N* HCl for 36 hours over a period of 5 days. After hydrolysis, each was evaporated to dryness in a vacuum, then twice treated with water and evaporated to remove the last of the HCl. The residue was taken up in water, made alkaline with MgO, and the $\text{NH}_3\text{-N}$ distilled into H_3BO_3 and titrated. The insoluble portion of the above residue (the humin) was filtered on a weighed sintered glass crucible and the filtrate made up to a definite volume. Van Slyke amino-nitrogen and total nitrogen determinations were made on aliquots of this filtrate. The humin was washed with dilute HCl to remove the inorganic salts, dried, weighed, and its nitrogen and ash contents were determined. The HCl washings were retained and analyzed for total nitrogen.

Methods of analysis

Suitable aliquots were removed from the various solid fractions and supernatant liquids, and total nitrogen was determined by a micro-Kjeldahl method using the Campbell and Hanna (4) digestion mixture and the H_3BO_3 titration procedure. For amino nitrogen the method used was that described by Van Slyke (20).

Total carbon was determined by dry combustion and absorption of the evolved CO_2 in $\text{Ba}(\text{OH})_2$ solution. The procedure described by Bartholomew and Norman (3), with some slight modifications, was used for the uronic acid determination.

The method of Clark (5) was used for the methoxyl determinations. The methoxyl content of the humate fractions was determined both before and after methylation. The humates were methylated with dimethyl sulfate by the method of Forsyth (6) except that one-tenth quantities of sample and reagents were used. The product was weighed after each methylation, and about 35 per cent

of the material remained after the fourth methylation, when the treatment was stopped for lack of material. About one third of the humate loss apparently was due to solution and the rest to mechanical loss and removal of material for methoxyl determination. Methylation was perhaps not complete, since the methoxyl content was higher after the fourth methylation than after the third.

For spectrographic analysis, the samples were dissolved in 100 ml. of 0.0004 *N* NaOH and diluted to a concentration of 0.001 per cent with water. Readings were taken on a Beckman spectrophotometer at the pH of the diluted solution

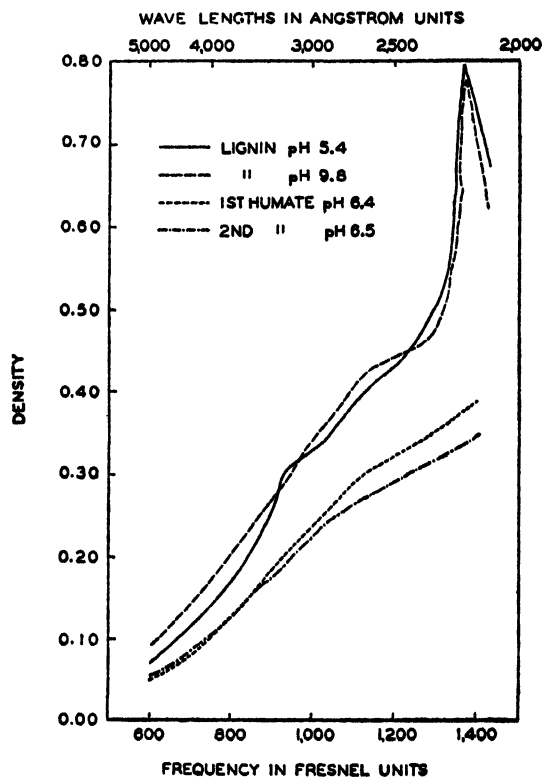


FIG. 1. ABSORPTION CURVES OF SOIL ORGANIC MATTER

(slightly acid) and also after the solution was made alkaline with NaOH. Typical absorption curves from this data are shown in figure 1, density being plotted against frequency in Fresnel units.

RESULTS AND DISCUSSION

Table 1 shows that the two humate fractions contained only 17.5 per cent of the carbon and 11.0 per cent of the nitrogen of the original soil, that 74.7 per cent of the carbon and 79.8 per cent of the nitrogen were left in the KCl floc and the soil residue, and that 7.8 per cent of the carbon and 9.2 per cent of the nitrogen were lost in the solutions.

Data for the analysis of the humate fractions are presented in table 2. The two fractions were very similar in carbon and nitrogen contents. It is interesting to note the similarity of these humates to a "dark compound" isolated from apricots by Weast and Mackinney (23) and said to have been formed by a reaction of the Maillard type between asparagine and/or aspartic acid and sugars. The uronic carbon expressed as percentage of total carbon was approximately 7

TABLE 1
Nitrogen and carbon distribution among the soil separates

	CARBON		NITROGEN	
	mgm./gm. soil	per cent of total C	mgm./gm. soil	per cent of total N
Original soil.....	62.0	100.0	6.74	100.0
1st Humate.....	5.38	8.7	0.39	5.8
2nd Humate.....	5.44	8.8	0.35	5.2
Residue.....	28.2	45.5	3.29	48.8
KCl floc.....	18.1	29.2	2.09	31.0
Total filtrates (by difference).....	4.9	7.8	0.62	9.2
Filtrates from saturating soil.....	—	—	0.26	3.9
Filtrates from 1st humate.....	—	—	0.25	3.7
Filtrates from 2nd humate.....	—	—	0.08	1.2

TABLE 2
Analysis of humate fractions
As per cent of ash-free, moisture-free material

	1ST HUMATE	2ND HUMATE
Carbon.....	53.6	53.5
Nitrogen.....	3.48	3.81
Ash.....	19.1	28.8
Uronic carbon.....	4.29	4.09
Methoxyl.....	0.83	0.63
Methoxyl after four methylations.....	7.63	8.45
Lignin.....	55.6	66.6
Nitrogen in lignin.....	3.04	3.03
Methoxyl in lignin.....	1.14	0.51
Ash in lignin.....	11.0	5.2

to 8 per cent and was lower than that usually reported in the literature; this may mean that uronic complexes are not precipitated by acid. Forsyth has reported the isolation of a polyuronide from the fulvic acid fraction of soil organic matter. The methoxyl content of the humates and of the lignin isolated from them was low in comparison with wood lignin, which contains more than 12 per cent. Moreover, not all of the methoxyl of the humate was found in the isolated lignin. The methoxyl content after methylation may not have given an accurate index of the amount of phenolic and alcoholic groups present, since

methylation may not have been complete. Also a considerable amount of the humate was dissolved by the treatment, and the material remaining after the fourth methylation may not have been strictly representative of the original humate.

The nitrogen content of the "lignin" was only slightly lower than that of the original humate. Lignin is considered to be a large and insoluble molecule, but before drying, the "lignin" was soluble in water. This raises the question of whether the isolated material was true lignin similar to that usually obtained from wood (9). Gottlieb and Hendricks (8) have reported that soil "lignin" is quite different from wood lignin in the products it yields on high-pressure hydrogenation or alkaline nitrobenzene oxidation.

The absorption spectra of the two humates and of lignin isolated from the first humate are shown in figure 1. The absorption spectra of the soil "lignin" had characteristics similar to those of lignin from other materials. There was a well defined maximum at 2,190A., but the band at 2,800A. may not be present,

TABLE 3
Nitrogen distribution on acid hydrolysis in humate materials
As mgm. N/gm. of humate material

	NH ₃ -N IN HYDRO- LYZATE	N IN FILTRATE		N IN HUMIN	N IN HCl WASHING OF HUMIN	TOTAL N	
		Total N	Amino N			Content	Recovery
1st humate....	3.84	4.33	3.39	11.17	1.63	25.7	21.0
2nd humate. . . .	4.28	5.82	3.35	10.37	0.92	24.0	21.4

although the curve showed a tendency to flatten out between 2,400A. and 2,800A. One might expect to find little evidence of this band if soil lignin consisted of fused ring structures (8), since this would likely restrict the "meta position freedom" (16). Patterson and Hibbert (17) found this band to be less well defined as the molecular complexity of the materials increased. The absorption of the humate fractions decreased as the wave length increased. The pH had little effect on the general shape of the absorption curve.

Results of the soil hydrolysis experiment are presented in table 3. Approximately half of the nitrogen of the fractions was in the humin form, that is, not made soluble by acid hydrolysis, and only about 16 per cent was amino nitrogen. This would seem to indicate that a considerable proportion of the nitrogen was not combined in the form of protein. The amounts of ash-free humin obtained from the humate fraction subjected to hydrolysis were 462 and 387 mgm. per gram for the first and second humate fractions respectively. Their nitrogen contents (11.17 and 10.37 mgm.) were 2.42 per cent and 2.68 per cent respectively.

SUMMARY AND CONCLUSIONS

In the treatment of soil humate fractions by a method frequently used to obtain lignin from plant material, a product was obtained that was different

in many respects from plant lignin: it was very low in methoxyl, high in nitrogen, soluble in water but insoluble in acid even when the acid solution was very weak. The ultraviolet light absorption curve of a solution of this material was similar in many respects, however, to that of lignin and related compounds, a fact which might be interpreted as indicating the aromatic character of the isolated material.

The union between lignin-derived material and nitrogenous compounds must have been very strong, since the nitrogen content of the isolated lignin was little lower than that of the humate from which it was obtained. This might indicate a more intimate union than would be expected between a protein molecule of high molecular weight and a large lignin molecule. The water-solubility of the "lignin" from the humate fraction would indicate that its molecular weight was not very high.

When the humate fractions were hydrolyzed, the proportion of amino-N to total N was lower than might have been expected if the soil nitrogen were combined largely as protein. Approximately half of the nitrogen was found in the humin and thus was not released on hydrolysis. The characteristics of these humates would seem to indicate that they were not simple lignoprotein complexes.

In general, the similarities between the humate fractions were more striking than the differences. The analytical results for carbon, nitrogen, and methoxyl; the distribution of the nitrogen on acid hydrolysis; the uronic acid and "lignin" contents; the methoxyl and nitrogen found in the "lignin"; and the absorption curves of the humates and of "lignin" derived from them were all similar although seldom identical. This would seem to support the idea that the analyses represented averages for a number of similar molecules and not percentages for any one humate molecule. In the humate fractions the amounts of these humus materials may have varied somewhat. It would appear that the differences in method required for the separation of the materials was due to the way they were combined in the soil rather than to any fundamental chemical differences in the materials themselves.

REFERENCES

- (1) ATKINSON, H. J., AND TURNER, R. C. 1944 Soil colloids: II. *Soil Sci.* 57: 233-240.
- (2) ATKINSON, H. J., TURNER, R. C., AND LEAHEY, A. 1944 Soil colloids: III. *Soil Sci.* 57: 243-246.
- (3) BARTHOLOMEW, W. V., AND NORMAN, A. G. 1941 The determination of uronic groups in soils and plant materials. *Iowa State Col. Jour. Sci.* 15: 253-260.
- (4) CAMPBELL, W. R., AND HANNA, M. I. 1937 The determination of nitrogen by modified Kjeldahl methods. *Jour. Biol. Chem.* 119: 1-7.
- (5) CLARK, E. P. 1932 The Viebock and Schwappach method for the determination of methoxyl and ethoxyl groups. *Jour. Assoc. Off. Agr. Chem.* 15: 136-140.
- (6) FORSYTH, W. G. C. 1946 The characterization of the humic complexes of soil organic matter. *Jour. Agr. Sci.* 37: 132-138.
- (7) GLADING, R. E. 1940 The ultra violet absorption spectra of lignin and related compounds. *Paper Trade Jour.* 111 (23): 33-39.
- (8) GOTTLIEB, S., AND HENDRICKS, S. B. 1946 Soil organic matter as related to the newer concepts of lignin chemistry. *Soil Sci. Soc. Amer. Proc.* (1945) 10: 117-125.

- (9) HEWSON, W. B., MCCARTHY, J. L., AND HIBBERT, H. 1941 Studies on lignin and related compounds: LVII. *Jour. Amer. Chem. Soc.* 63: 3041-3045.
- (10) HOBSON, R. P., AND PAGE, H. J. 1932 Studies on the carbon and nitrogen cycles in the soil: VII. *Jour. Agr. Sci.* 22: 497-515.
- (11) KOJIMA, R. T. 1947 Soil organic nitrogen: I. *Soil Sci.* 64: 157-165.
- (12) KOJIMA, R. T. 1947 Soil organic nitrogen: II. *Soil Sci.* 64: 245-252.
- (13) MANNING, K. R., AND DELONG, W. A. 1941 The lignin content of some common vegetables with observations on methods for the determination of lignin. *Sci. Agr.* 22: 69-79.
- (14) MATTSO, S., AND KOUTLER-ANDERSSON, E. 1943 The acid-base condition of vegetation, litter and humus: VI. *Ann. Agr. Col. Sweden* 11: 107-134.
- (15) MORROW, C. A., AND GORTNER, R. A. 1917 The organic matter of the soil. V. *Soil Sci.* 3: 297-331.
- (16) PATTERSON, R. F., AND HIBBERT, H. 1943 Studies on lignin and related compounds: LXXII. *Jour. Amer. Chem. Soc.* 65: 1862-1869.
- (17) PATTERSON, R. F., AND HIBBERT, H. 1943. Studies on lignin and related compounds: LXXIII. *Jour. Amer. Chem. Soc.* 65: 1869-1873.
- (18) STAMM, A. J., SEMB, J., AND HARRIS, E. E. 1932 Absorption spectra of lignin solutions. *Jour. Phys. Chem.* 36: 1574-1584.
- (19) TYULIN, A. T. 1938 The composition and structure of soil organo-mineral gels and soil fertility. *Soil Sci.* 45: 343-357.
- (20) VAN SLYKE, D. D. 1914 The gasometric determination of aliphatic amino nitrogen in minute quantities. *Jour. Biol. Chem.* 16: 121-124.
- (21) WAKSMAN, S. A., AND IYER, K. R. N. 1932 Contribution to our knowledge of the chemical nature and origin of humus: I. *Soil Sci.* 34: 43-69.
- (22) WAKSMAN, S. A. 1936 *Humus*. Bailliere, Tindall and Cox, London.
- (23) WEAST, C. A., AND MACKINNEY, G. 1941 Nonenzymatic darkening of fruits and fruit products. *Indus. and Engin. Chem.* 33: 1408-1412.

NITRITE INJURY ON AVOCADO AND CITRUS SEEDLINGS IN NUTRIENT SOLUTION¹

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In connection with recent studies on oxygen requirements of avocado and citrus seedlings (3), small amounts of nitrites were found in some of the cultures maintained at low oxygen levels. Exploratory work was therefore carried out to observe the extent of nitrite accumulations in such cultures and to study the toxic effects of different nitrite concentrations on avocado and citrus seedlings grown in nutrient solution at various pH levels.

EXPERIMENTAL PROCEDURE AND RESULTS

For these experiments, avocado (Dickinson variety) and sweet orange seedlings were germinated in river-bottom sand and then selected for uniformity in size and vigor and carefully transferred to 25-liter Pyrex battery jars filled with a well-aerated full nutrient solution (solution 1, table 1). The seedlings were grown in these jars (at pH 5.5) for several days, until new root growth had begun, before further treatment.

Accumulation of nitrites in nutrient solutions kept at low oxygen level

Avocado seedlings, grown as described above, were placed in duplicate 20-liter Pyrex bottles containing, respectively, each of the three nutrient solutions shown in table 1. Each bottle was covered with brown wrapping paper, to exclude light, and was fitted with a two-hole rubber stopper to hold the seedling and the aeration tube in place with a minimum of oxygen contamination from the atmosphere.

Dissolved oxygen was driven out of the culture solution by bubbling with a commercial grade of compressed nitrogen gas. Oxygen determinations were then made by the Winkler method (1). The small amount of oxygen remaining in the solution (up to 0.05 ppm.) is attributed to contamination from the atmosphere, since solutions that were more tightly sealed during the bubbling process showed no oxygen.

In half the cultures (table 2), the seedlings were kept in place throughout the experiment; in the other half, they were removed after the second day of the low-oxygen regime. After observations had been made for 10 days, 5 gm. of organic matter (oatmeal) was added as shown in table 2 and observations were continued for another 10 days.

As mentioned, three different solutions (table 1) were used to determine the effect of available nitrogen on nitrite accumulation. In solution 1, nitrogen was available as NO_3 ; in solution 2, nitrogen was available as NH_4 ; and in

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solution 3, nitrogen was omitted. Daily samples were taken from each culture for nitrite determinations, which were run colorimetrically with sulfanilic acid and alpha-naphthalamine reagents (1).

No appreciable amounts of nitrites accumulated except in those cultures in which nitrogen was available in the form of NO_3 (table 2). Nitrite concentrations were increased by the presence of avocado seedlings and by the addition of organic matter. When organic matter was added in the form of oatmeal, nitrites increased and then decreased again within the next few days.

The maximum nitrite concentration in cultures containing no nitrogen, or containing nitrogen in the form of NH_4 , was 0.4 ppm. Where nitrogen was available as NO_3 and the avocado roots remained in the culture, the maximum nitrite concentration was 4.0 ppm. before adding oatmeal, and 8.2 ppm. afterward. Where the avocado plants were removed from the cultures at the end of the second day of the low-oxygen regime, the maximum nitrite then developed was 0.4 ppm. When, however, oatmeal was added to these plantless culture solutions the nitrite rose to 4.0 ppm. in 2 days and then diminished.

TABLE 1
Composition of nutrient solutions

SOLUTION NUMBER	SOURCE OF NITROGEN	CONSTITUENTS														
		Milliequivalents per liter									Parts per million					
		NO ₃	NH ₄	Ca	Mg	K	SO ₄	PO ₄	Na	Cl	B	Mn	Al	Zn	Fe*	Cu
1	NO ₃	5.0	0.0	6.0	2.0	2.0	4.0	1.0	0.1	0.1	0.50	0.50	0.50	0.50	0.10	0.01
2	NH ₄	0.0	5.0	1.0	2.0	2.0	9.0	1.0	0.1	0.1	0.50	0.50	0.50	0.50	0.10	0.01
3	None	0.0	0.0	1.0	2.0	2.0	4.0	1.0	0.1	0.1	0.50	0.50	0.50	0.50	0.10	0.01

* Iron was added as ferrous sulfate three times weekly at the rate of 0.10 ppm.

These data show that nitrite development in low-oxygen culture solutions is stimulated by the presence of plant roots; it appears that enough organic matter is present or exuded from plant roots to provide energy material for the denitrifiers. When more organic matter is added, nitrite formation is increased over that capable of being formed in the presence of plant roots.

As described in previous studies (3), in all the low-oxygen cultures avocado root tips became shrunk or constricted in the region of cell elongation, and light shades of yellow, pink, and purple appeared during the first 2 days of treatment, with darker discoloration following several days later.

During the first day of treatment, the immature leaves passed through a period of temporary wilting, after which normal turgor was restored. After several days, the seedlings that were left in the cultures started to wilt again, but this time wilting continued to increase until all the leaves hung in a vertical position and the seedlings finally died. The seedlings that had been removed from treatment after the second day were placed in well-aerated full nutrient solutions, where they produced new root growth and continued to grow without further wilting.

The question that arose following these findings was whether the injury noted was due to low oxygen *per se* or was the result of nitrite formation in these cultures. To obtain information on this question, experiments as described in the following sections were set up to determine the relative tolerance of

TABLE 2
Nitrite accumulation in nutrient solutions kept at low oxygen level
(20-day treatment at pH 5.5)

CULTURE NUMBER	OXYGEN SUPPLY		SOURCE OF NITROGEN	ORGANIC MATTER*	NITRITE CONCENTRATION IN NUTRIENT SOLUTION					
	Minimum	Maximum			1st day	5th day	10th day	12th day	15th day	20th day
	ppm.	ppm.			ppm.	ppm.	ppm.	ppm.	ppm.	ppm.
<i>Avocado seedlings grown continuously in cultures</i>										
1	0.01	0.04	NO ₂	5.0	0.0	3.2	4.0	8.2	3.2	2.0
2	0.00	0.05	NO ₂	5.0	0.0	3.4	3.8	8.0	3.0	2.0
3	0.02	0.04	NO ₂	None	0.0	3.2	4.0	4.0	0.6	0.0
4	0.00	0.04	NO ₂	None	0.0	3.2	4.0	3.6	0.4	0.0
5	0.00	0.05	NH ₄	5.0	0.0	0.0	0.0	0.0	0.0	0.0
6	0.00	0.04	NH ₄	5.0	0.0	0.2	0.0	0.0	0.0	0.0
7	0.02	0.05	None	5.0	0.0	0.2	0.2	0.0	0.0	0.0
8	0.01	0.05	None	5.0	0.0	0.2	0.4	0.0	0.0	0.0
<i>Avocado seedlings removed from cultures after second day</i>										
9	0.01	0.04	NO ₂	5.0	0.0	0.2	0.2	3.8	1.4	0.0
10	0.02	0.04	NO ₂	5.0	0.0	0.4	0.2	4.0	2.0	0.2
11	0.01	0.05	NO ₂	None	0.0	0.4	0.2	0.2	0.0	0.0
12	0.00	0.04	NO ₂	None	0.0	0.4	0.2	0.2	0.0	0.0
13	0.02	0.05	NH ₄	5.0	0.0	0.4	0.2	0.0	0.0	0.0
14	0.00	0.04	NH ₄	5.0	0.0	0.4	0.4	0.0	0.0	0.0
15	0.02	0.05	None	5.0	0.0	0.2	0.4	0.0	0.0	0.0
16	0.02	0.04	None	5.0	0.0	0.2	0.4	0.0	0.0	0.0

* Organic matter added as dry oatmeal after sampling for nitrites on the 10th day.

avocado and (for comparison) citrus seedlings to various nitrite concentrations.

Effects of different nitrite concentrations on seedlings grown at pH 5.5

The well-aerated full nutrient solution in each of eight 25-liter Pyrex battery jars was adjusted to pH 5.5. Three avocado seedlings and three citrus seedlings were then carefully transferred to each culture, where they were grown for several days before further treatment. As soon as new root growth had begun, nitrite additions ranging from 0 to 100 ppm. were made from a stock solution of sodium nitrite (table 3), and the various nitrite levels were kept constant by daily analyses and adjustments. After an observation period of 10 days, the

cultures were refilled with new solution, free of nitrites, and observations were continued.

Root injury. At nitrite concentrations of 5 ppm. or less, there was no injury to either avocado or citrus roots, and the seedlings grew with good to excellent vigor; but at 10 ppm., a few dead root tips were detected on both avocado and citrus after the first day of treatment.

At higher nitrite concentrations, injury was more pronounced and increased as the time of exposure was increased through about 6 days, after which no further difference could be detected. In all cultures injury appeared to be more severe on the avocado seedlings than on the citrus.

Avocado injury was characterized by dark-brown discolorations which appeared first at the root tips and then spread in uneven patterns along the fleshy

TABLE 3

Response of avocado and citrus seedlings to different nitrite concentrations in nutrient solution (10-day treatment at pH 5.5)

CULTURE NUMBER	NITRITE NITROGEN IN SOLUTION	AVOCADO			CITRUS		
		Root injury	Leaf wilt	New root growth (recovery) after treatment*	Root injury	Leaf wilt	New root growth (recovery) after treatment*
	ppm.						
1	0	None	None	Excellent	None	None	Excellent
2	1	None	None	Excellent	None	None	Excellent
3	2	None	None	Excellent	None	None	Excellent
4	5	None	None	Good	None	None	Good
5	10	Slight	None	Fair	Slight	None	Fair
7	20	Moderate	Slight	Poor	Slight	None	Poor
7	50	Severe	Severe	None	Moderate	Slight	Poor
8	100	Severe	Severe	None	Severe	Slight	Poor

* After the 10-day treatment with nitrite nitrogen, the cultures were refilled with solution 1, free of nitrites, and observations were continued.

white feeder roots. The light shades of yellow, pink, and purple were lacking, and there were no root constrictions, as previously described in connection with oxygen deficiency (3). Injured citrus roots became very soft and pliable but kept their normal color for a few days, then turned orange-yellow and finally began to slough off. The appearance of nitrite injury on roots of citrus seedlings was not essentially different from the injury described in previous studies (3) as caused by oxygen deficiency.

Leaf wilt. Avocado leaves became slightly wilted 1 day after exposure to nitrite concentrations of 20, 50, and 100 ppm. (table 3), but at 20 ppm. the leaves were rescued from further wilting as soon as new roots appeared. At 50 and 100 ppm., new root growth was lacking, wilting increased in severeness, and the seedlings finally died.

Leaves of citrus seedlings were slightly wilted after 1 day's exposure to nitrite concentrations of 50 and 100 ppm. but they regained their normal turgor during the next few days and continued to grow without further wilting.

Recovery after treatment. After the 10-day treatment at different nitrite concentrations, all cultures were given a freshly mixed nutrient solution (No. 1,

TABLE 4

Effect of nitrite additions on avocado and citrus seedlings grown in nutrient solution at different pH levels
(10-day treatment)

pH	AVOCADO				CITRUS			
	Nitrite nitrogen added to solution				Nitrite nitrogen added to solution			
	0 ppm.	5 ppm.	10 ppm.	20 ppm.	0 ppm.	5 ppm.	10 ppm.	20 ppm.
<i>Root injury</i>								
4.0	None	Moderate	Severe	Severe	None	Slight	Moderate	Moderate
4.5	None	Moderate	Moderate	Severe	None	Slight	Slight	Moderate
5.0	None	Slight	Moderate	Severe	None	Slight	Slight	Slight
5.5	None	None	Slight	Moderate	None	None	Slight	Slight
6.0	None	None	None	Slight	None	None	None	Slight
7.0	None	None	None	None	None	None	None	None
<i>Leaf wilt</i>								
4.0	None	Slight	Severe	Severe	None	None	None	None
4.5	None	Slight	Slight	Severe	None	None	None	None
5.0	None	None	Slight	Severe	None	None	None	None
5.5	None	None	None	Slight	None	None	None	None
6.0	None	None	None	None	None	None	None	None
7.0	None	None	None	None	None	None	None	None

New root growth (recovery, after specified nitrite treatment) in fresh solution without nitrites

4.0	Excellent	Poor	None	None	Excellent	Fair	Poor	Poor
4.5	Excellent	Poor	Poor	None	Excellent	Good	Fair	Poor
5.0	Excellent	Fair	Poor	None	Excellent	Good	Fair	Poor
5.5	Excellent	Good	Fair	Poor	Excellent	Good	Fair	Poor
6.0	Excellent	Good	Good	Fair	Good	Good	Good	Fair
7.0	Good	Good	Good	Good	Good	Good	Good	Good

table 1), and nitrites were omitted. Subsequent root growth in the first three cultures (table 3), in which the nitrite concentration did not exceed 2 ppm., continued to be excellent. Growth was good but not excellent after exposure at 5 ppm., fair at 10 ppm., and poor at 20 ppm. After treatment at 50 and 100 ppm., avocado roots failed to grow, and the seedlings died. Roots of citrus seedlings grew after treatment at all nitrite concentrations, including 100 ppm.

Effects of nitrite additions on seedlings grown at different pH levels

The well-aerated full nutrient solution in each of six 25-liter battery jars was adjusted to various pH levels, as shown in table 4. Three avocado and three citrus seedlings were then transferred to each culture, where they were grown for several days before further treatment. As soon as new root growth had begun, nitrite additions of 5, 10, and 20 ppm. were made from a stock solution of sodium nitrite, and the various nitrite levels were kept constant by daily analyses and adjustments. After 10 days, the cultures were refilled with new solution from which nitrites had been omitted, and observations were continued.



FIG. 1. ROOTS OF AVOCADO SEEDLINGS GROWN IN CULTURE SOLUTIONS AT pH 5.5

Left to right: solutions containing 0, 5, 10, and 20 ppm. nitrite nitrogen. Photographed 10 days after treatment.

The avocado seedlings suffered more damage in the presence of nitrites than the citrus seedlings, as shown by more extensive root injury, more severe leaf wilt, and less ability to revive with the production of new root growth after treatment (table 3).

Root injury. Root injury due to the presence of nitrite nitrogen increased as the pH level decreased and was most apparent at the highest nitrite concentration. Dead root tips were found at pH 4.0 to 4.5 after 1 day's exposure to nitrite concentrations of 10 and 20 ppm. A few days later, injury occurred at nitrite concentrations as low as 5 ppm. at pH 4.0 to 5.0. At higher pH levels, the rate and extent of injury decreased until a nitrite concentration of 20 ppm. produced only slight injury at pH 6.0 and no injury whatever at pH 7.0.

Nitrite injury caused avocado root tips to turn dark brown. Root tips of citrus seedlings became very soft and pliable, and several days after injury the roots turned orange-yellow and sloughed off.

Leaf wilt. As in the preceding experiment, wilting of avocado leaves was closely associated with root injury, and leaf recovery was closely associated with production of new root growth. Slight wilting of the leaves followed moderate root injury, but as soon as new roots were produced, wilting ceased and the



FIG. 2. ROOTS OF CITRUS SEEDLINGS GROWN IN CULTURE SOLUTIONS AT pH 5.5

Left, without nitrites; right, with 20 ppm. nitrite nitrogen. Photographed 10 days after treatment.

normal turgor of the leaves was gradually restored. Where the roots were severely injured and new roots failed to grow, the leaves became severely wilted and the seedlings died.

Leaves of citrus seedlings kept their normal appearance and did not wilt at nitrite concentrations ranging from 0 to 20 ppm., although, as previously mentioned in connection with table 3, citrus leaves showed slight wilting at nitrite concentrations of 50 and 100 ppm. in culture solutions adjusted to pH 5.5.

Recovery after treatment. Recovery of plants from nitrite injury, as shown by

new root growth after treatment, increased as the pH level of the solution increased, and recovery was better after exposure to low concentrations of nitrite than after exposure to high concentrations.

At pH 4.0, avocado roots failed to grow after exposure to nitrite concentrations as low as 10 ppm. and produced only poor growth at 5 ppm. After treatment at 20 ppm., avocado root growth was lacking at pH 4.0 to 5.0, poor at pH 5.5, fair at pH 6.0, and good at pH 7.0. Avocado root growth in solutions containing different nitrite concentrations is compared in figure 1.

Citrus seedlings recovered and produced new root growth after all treatments, although the rate of growth decreased at the lower pH levels and the roots became rather short and stubby, with frequent branching near the tips (fig. 2).

DISCUSSION

Nitrite accumulation

According to Greaves, Stewart, and Hirst (6), the maximum nitrite concentration in irrigated fields in Utah did not exceed 17 pounds per acre; Feher and Vagi (4) found 0.27 to 1.14 mgm. nitrite per kilogram in the alkaline soils of Hungary; and Janssen and Metzger (7), working with potted rice soils in Arkansas, found a maximum of 0.25 ppm. Sokloff and Klotz (11) reported various nitrite concentrations, up to 70 ppm., on well-drained Ramona loam soils of California, after rather heavy applications of organic matter and NO_3 nitrogen. Various microorganisms were indicated as the active denitrifiers, and other substances, in addition to NO_2 , were listed as respiratory poisons.

Larger quantities of NO_2 nitrogen are reported by Fraps and Sterges (5) in cultures of soil containing sulfate of ammonia and also in soil cultures which did not receive additions of nitrogenous materials. NO_2 production was slow during the first week, increased rapidly during the second and third weeks, and decreased rather sharply after the fourth week. Similar fluctuations were observed in the present studies, but maximum values were reached in a shorter time. The influence of NO_3 and organic matter on NO_2 accumulations (table 2) indicates that active denitrifiers utilize energy released from the organic matter to speed up NO_2 production.

Nitrite injury

Nitrite injury has been reported by Birner and Lucanus (2), who found that the roots of oat seedlings became yellow in a nutrient solution containing 0.25 per cent KNO_2 , and after 8 to 10 days the plants died. Schultz (10) observed that in dilute solutions nitrites seemed to be more easily absorbed by plants than nitrates; and, according to Stutzer (12), a dilute solution of nitrites seemed to be beneficial to some plants and injurious to others. Perciabosco and Rosso (9) found that plants accumulated higher percentages of nitrogen when supplied with nitrites than when given the same concentration of nitrate, but Feher and Vagi (4) found that large quantities of nitrites exerted an initial inhibition on plant growth. Sokoloff and Klotz (11) reported severe injury to the roots of

citrus trees grown on slightly alkaline California soils containing 40 ppm. NO_2 , and, in some cases, less than 40 ppm.

The work of Mevius and Dikussar (8) shows that the concentration of nitrite that can be tolerated by sweet corn seedlings depends upon the pH of the nutrient solution. The report shows normal growth at pH 4.0 in the presence of 1 mgm. NaNO_2 per liter, but wilting and root injury in the presence of 2 mgm.; at pH 5.0, the seedlings withstood 10 mgm., but not 20 mgm., without injury; at pH 6.4, they withstood 100 mgm., but not 200 mgm., without injury; and at pH 7.0, there was no injury in the presence of 200 mgm. The tendency for plants to withstand increasingly higher nitrite concentrations as the pH level is increased is confirmed by the work reported herewith. The sweet corn seedlings, however, withstood higher nitrite concentrations at specific pH levels than did the avocado and citrus seedlings. For example, at pH 5.0 the sweet corn seedlings withstood 10 ppm. NO_2 , whereas avocado and citrus seedlings could not withstand 5 ppm. These differences are attributed to variations in plant types, since they are so widely separated in phylogenetic relationships and have evolved under different climatic conditions.

It is apparent that a deficiency of oxygen in the nutrient solution may cause two types of injury: first, direct injury by suffocation of the feeder roots; and second, indirect injury by respiratory poisons, such as nitrites, which are produced by microorganisms. The two types of injury are easily distinguished on avocado seedlings but not on citrus.

SUMMARY

Three experiments are reported, showing (a) the accumulation of nitrites in nutrient solutions kept at low oxygen level, (b) the toxic effects of different nitrite concentrations on avocado and citrus seedlings grown at pH 5.5, and (c) the toxic effects of nitrite additions on avocado and citrus seedlings grown at different pH levels.

There was no appreciable accumulation of nitrites except in solutions containing N as NO_3 . With NO_3 available, nitrites increased as a result of the presence of avocado seedlings and the addition of organic matter. The maximum nitrite concentration, where the seedlings were present, was 4.0 ppm. before the addition of organic matter and 8.2 ppm. after the addition of 5 gm. of oatmeal to a 20-liter culture solution.

Seedlings withstood increasingly higher nitrite concentrations at higher pH levels. For example, 5 ppm. NO_2 nitrogen caused injury to avocado and citrus root tips at pH 5.0 but not at pH 5.5; 10 ppm. caused injury at pH 5.5 but not at pH 6.0; 20 ppm. caused injury at pH 6.0 but not at pH 7.0. Avocado seedlings were more severely injured than citrus seedlings and showed less ability to recover from injury with the production of new root growth after treatment.

REFERENCES

- (1) Association of Official Agricultural Chemists. 1945 Official and Tentative Methods of Analysis, ed. 6. Washington, D. C.

- (2) BIERNER, H., AND LUCANUS, B. 1866 Wasserkulturversuch mit Hafer. *Landw. Vers. Sta.* 8: 128-134.
- (3) CURTIS, D. S. 1949 Effect of oxygen supply in nutrient solution on avocado and citrus seedlings. *Soil Sci.* 67: 253-260.
- (4) FEHER, D., AND VAGI, I. 1926 The influence of nitrites on the growth of plants. *Biochem. Ztschr.* 174: 262-270. [Abstract in *Chem. Abs.* 21: 942. 1927.]
- (5) FRAPS, G. S., AND STERGES, A. J. 1930 Occurrence of nitrites in soils. *Tex. Agr. Exp. Sta. Bul.* 412: 1-15.
- (6) GREAVES, J. E., STEWART, R., AND HIRST, C. T. 1917 Nitrous nitrogen in irrigated soils. *Soil Sci.* 3: 149-154.
- (7) JANSSEN, G., AND METZGER, W. H. 1928 Transformations of nitrogen in rice soil. *Jour. Amer. Soc. Agron.* 20: 459-476.
- (8) MEVIUS, W., AND DIKUSSAR, I. 1930 Nitrite als Stickstoffquellen für höhere Pflanzen. *Jahrb. Wiss. Bot.* 73: 633-703.
- (9) PERCIABOSCO, P., AND ROSSO, U., 1909 L'assorbimento diretto dei nitriti nelle piante. *Staz. Sper. Agr. Ital.* 42: 5.
- (10) SCHULTZ, M. 1903 Studien über den Einfluss von Nitriten auf die Keimung von Samen und auf das Wachstum von Pflanzen. Königsberg. (Diss.)
- (11) SOKOLOFF, V. P., AND KLOTZ, L. J. 1943 Decline and collapse of citrus trees in relation to nitrite in orchard soils. *Calif. Citrogr.* 28: 290, 308.
- (12) STUTZER, A. 1906 Die Wirkung von Nitrit auf Pflanzen. *Jour. Landw.* 54: 125.

EFFECT OF EXCHANGEABLE MAGNESIUM ON THE CHEMICAL AND PHYSICAL PROPERTIES OF SOME ARIZONA SOILS¹

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A high content of exchangeable magnesium has been given as the reason for the unfavorable physical properties of some soils (6, 8, 11), as well as a factor contributing to the development of the solonetz structure (9, 10, 12). Certain nonproductive soils of northern Arizona which exhibit notably poor structure and permeability to water have been found to contain an unusually high percentage of their magnesium in the exchangeable form. This observation led to an investigation of the areas where such soils occur, the source of the magnesium in the soils, and the part that magnesium apparently plays in adversely affecting their physical properties.

CHARACTER OF SOILS INVESTIGATED

Two high-magnesium soils representing large acreages in northern Arizona and tentatively classified as the Mingus and Joseph series, were chosen for this study. Both are recent alluvial soils but widely separated and of different origin. The Mingus soil is derived primarily from magnesian limestones and shales. The Joseph soil consists of a deep deposit of disintegrated calcareous, high-magnesium Chinle shale transported into the Hunt Valley from the nearby badlands of the Zuni River. Neither of these soils exhibits evidences of profile development, and the solonetz structure is entirely absent.

For this study a field on the Mingus series was chosen near the town of Camp Verde in Yavapai County; at one end was an excellent stand of alfalfa and at the other a poor stand, exhibiting signs of distress. The farm on the Joseph series was adjacent to the Little Colorado River near the town of St. Johns; at the time of sampling it was in pasture and the vegetation was mostly alkali weeds.

EXPERIMENTAL PROCEDURE

Physical methods

Since the primary structural difficulty in these soils was manifested by their unusual impermeability to water, some physical determinations were made to gain an insight into the magnitude of the effect. *Mechanical analyses* were made by the Bouyoucos hydrometer method. *Moisture equivalent* was determined by the conventional centrifuge method. *Capillary rise* determinations according to the method of Gardner (5) were made on samples of soil compacted uniformly into glass tubes 1.6 cm. in diameter and 60 cm. long. The bottom ends of the

¹ Presented at the annual meeting of the Soil Science Society of America, Ft. Collins, Colorado, August 24-27, 1948.

tubes were fitted with notched 2-hole rubber stoppers and covered with wire gauze fine enough to retain the soil. The columns of soil so prepared were placed in small beakers of water to a depth of 5 cm., and the rise of water in the columns was noted at the end of 1, 3, and 20 hours. *Percolation rate* determinations were made on 100-gm. samples of soil compacted uniformly into percolation tubes 3 cm. in diameter and 23 cm. long, the soil being retained by fine wire gauze. The head of water above the soil column was maintained constant at 2 cm. The volume of water percolating through the column was determined after convenient intervals of time. Percentage of *colloidal matter* was determined by moisture sorption over 3.3 per cent H_2SO_4 .

Chemical methods

Determinations of pH were made with the Beckman pH meter on both the soil paste and the 1:10 soil: water suspension, the difference between these values giving the hydrolytic pH value. *Soluble salt* content was determined by evaporation of the aqueous soil extract. *Base-exchange capacity* was determined by saturation with ammonium ion, distillation of the ammonia so held, and titration. In the solution obtained, the *individual exchangeable bases* were determined by replacing them with ammonium ion, by accepted methods, and calculating exchangeable calcium by difference. *Mineral content* of the colloidal clay was determined by the thermal method of Hendricks *et al.* (7) as modified by Buehrer *et al.* (3). Ultimate analysis of the calcium-saturated colloidal clay was made by conventional methods after sodium carbonate fusion.

RESULTS WITH MINGUS AND JOSEPH SOILS

The mechanical analyses of the soils studied are given in table 1. The clay content of the "poor" Mingus soil ranged between 60 and 89 per cent within the profile and averaged about 70 per cent. That of "good" Mingus soil at the productive end of the field averaged about 35 per cent and was relatively uniform throughout the profile. The Joseph soil had a clay content ranging between 70 and 81 per cent clay and in this respect was similar to the unproductive Mingus soil. In all of these soils the percentage of colloid was unusually high.

The results of the percolation rate studies are shown in figure 1. Determinations were made on samples of surface soil represented by the top 6 inches and on subsoil samples taken at a depth of 18 to 30 inches in the Mingus profile and 26 to 72 inches in the Joseph profile. The curves show that the poor productivity may be due in part to the inability of these soils to take water and to poor internal drainage. The "good" Mingus soil gave high percolation rates, practically identical for surface and subsoil. The "poor" Mingus soil exhibited a much slower rate of percolation, the surface showing a much slower rate than the subsoil, notwithstanding its considerably lighter texture. The Joseph soil, particularly the subsoil, gave a much slower percolation rate.

The capillary rise data are shown in figure 2 and correlate closely with those obtained by percolation. The unproductive ("poor") soils exhibited a much smaller capillary rise than the productive; this was especially true of the Joseph

surface and subsoil. If the relative magnitude of the capillary rise is related to, or a measure of, differences in structure as set forth by Gardner (5), then the nonproductivity of the poor Mingus and Joseph soils must be due, in part at least, to poor structural condition.

Chemical studies were made in a further attempt to explain the behavior of these soils. The base-exchange status of the soils is shown in table 2. The high base-exchange capacity of the two "poor" soils is to be expected from their high clay contents. The most striking characteristic of these soils, however, in relation

TABLE 1
Mechanical analyses of Mingus and Joseph soils*

SOIL	DEPTH	SAND	SILT	CLAY	COLLOID†
	<i>inches</i>	<i>per cent</i>	<i>per cent</i>	<i>per cent</i>	<i>per cent</i>
Mingus (poor)	0-6	5.6	31.2	63.2	53.6
	6-18	1.6	31.4	67.0	—
	18-30	0.6	10.2	89.2	55.8
	30-48	11.6	28.2	60.2	—
	48-66	0.0	30.0	70.0	—
Mingus (good)	0-6	23.4	38.6	38.0	40.9
	6-18	30.4	36.0	33.6	—
	18-30	35.4	33.8	30.8	48.1
	30-48	31.4	31.8	36.8	—
	48-66	32.4	32.0	35.4	—
Joseph (poor)	0-2	12.4	18.0	69.6	58.8
	2-6	10.4	13.2	76.4	—
	6-16	11.6	7.4	81.0	—
	16-26	10.4	19.0	70.6	—
	26-72	9.6	15.0	75.5	71.7
	72-102	11.6	14.0	74.4	—

* By hydrometer method.

† By moisture sorption over 3.3 per cent H_2SO_4 .

to their exchangeable bases is the remarkably high content of exchangeable magnesium in comparison with sodium, potassium, and calcium. In the Mingus soil more than half of the entire base-exchange capacity is exchangeable magnesium. These results confirm those of McGeorge² and of Caster and led to the original inference that the poor physical condition of these soils was due to their high exchangeable magnesium content. In general, the amount of exchangeable calcium in desert soils is considerably greater than that of magnesium. In the Mingus soil, the reverse is true. Another striking fact is that the amounts of exchangeable sodium and potassium in this soil are relatively small. The impervious Joseph clay, on the other hand, shows a predominance of calcium in the exchange com-

² Unpublished results.

plex together with appreciable amounts of exchangeable sodium. It seemed probable in the latter case that the poor permeability may have been due to the combined effect of high exchangeable magnesium content, exchangeable sodium, and an unusually high colloidal clay content, and hence not attributable to exchangeable magnesium alone.

Soluble salts

Since these soils exhibit poor internal drainage, it was believed that the resulting accumulation of soluble salts might be partly responsible for their poor

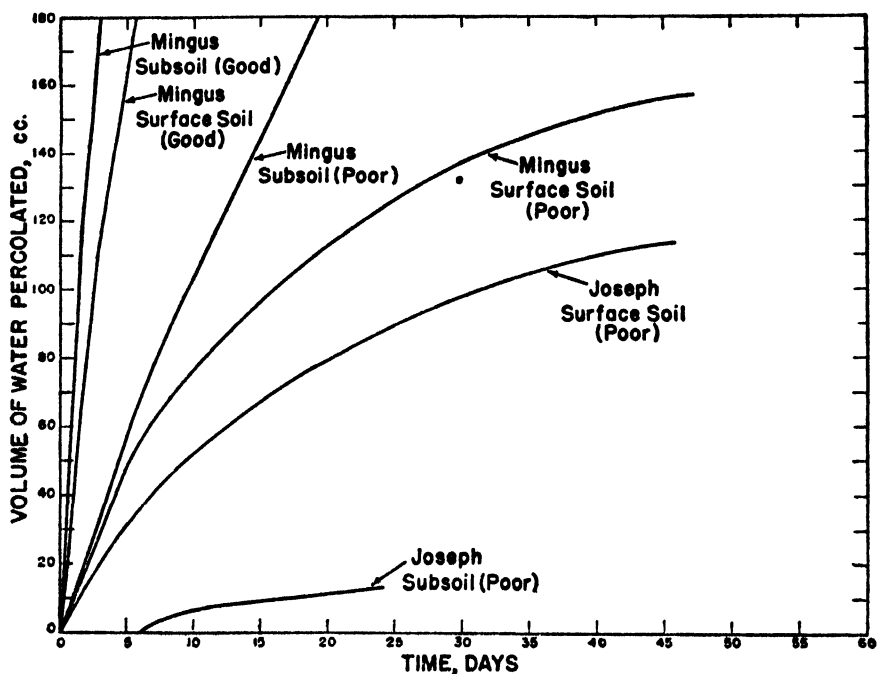


FIG. 1. RATE OF PERCOLATION OF WATER THROUGH COLUMNS OF MINGUS AND JOSEPH SOILS

productivity. Hence a detailed study of the soluble salt content, cations and anions present, and pH was made. The results are given in table 3. The total salt contents of successive strata in the Mingus profile are similar to those usually found in desert soils and considerably below the limit at which crop growth on clay soils is adversely affected. The "poor" Mingus soil is appreciably higher in total salt content than the "good." In the Joseph soil, on the other hand, the salinity was excessively high at all levels and increased rapidly with depth. It is so excessive, in fact, as to be toxic to crop plants, especially in view of the high sodium and chloride contents. It would be expected that such high concentrations of soluble salts would flocculate the soil colloids and thus improve permeability, but as shown in figures 1 and 2, the Joseph soil is exceedingly impermeable

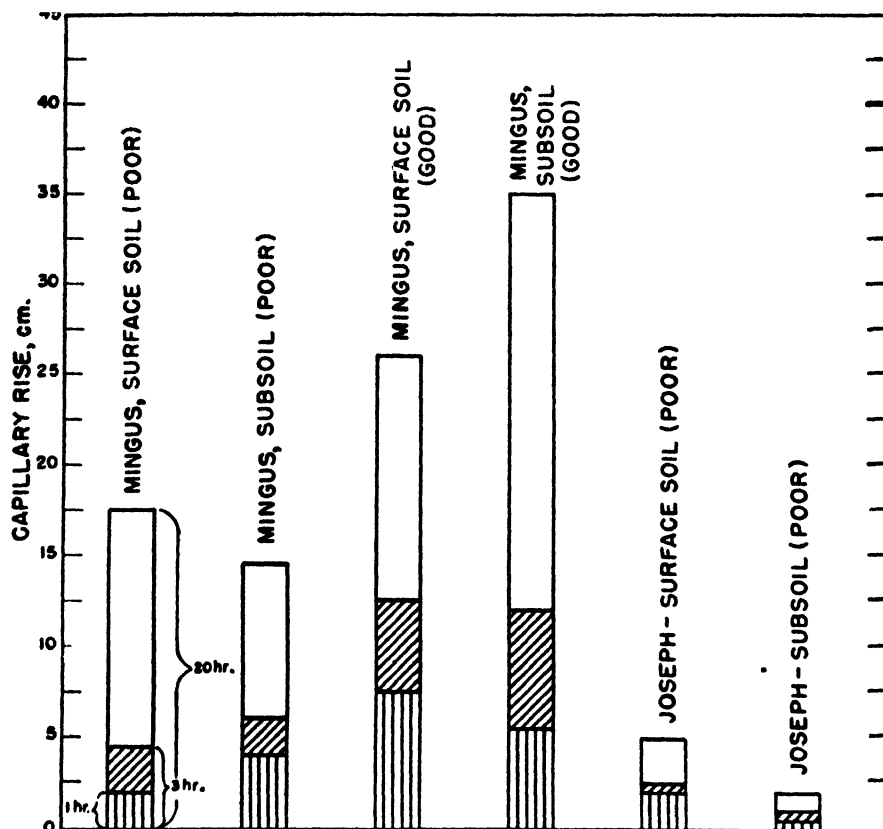


FIG. 2. RATE OF CAPILLARY RISE OF WATER IN COLUMNS OF MINGUS AND JOSEPH SOILS

TABLE 2

Base-exchange capacity and exchangeable bases of Mingus and Joseph soils

	DEPTH	BASE EXCHANGE CAPACITY	EXCHANGEABLE BASES			
			Mg	Na	K	Ca*
Mingus (poor)	inches	me.†	me.†	me.†	me.†	me.†
	0-6	40.47	20.46	0.92	2.18	16.91
	30-48	40.00	27.81	0.97	1.45	9.77
Mingus (good)	0-6	29.52	14.91	0.78	1.42	12.41
	48-66	31.37	19.75	0.75	1.13	9.74
Joseph (poor)	0-2	50.47	11.85	4.24	2.28	32.10
	30-72	59.32	14.72	6.70	2.02	35.88

* By difference.

† Per 100 gm. of soil

and hence appears to exhibit a single-grain structure. Obviously, such a soil would be very difficult to leach free of its soluble salts.

pH Relationships

The pH data in table 3 indicate alkalinity not exceeding pH 8, which is consistent with the total absence of free carbonate ion in the soil solution. This degree of alkalinity is not sufficient to cause dispersion of the colloidal clay. In fact the pH conditions which exist in these soils at field moisture contents are ideal for crop growth. The presence of exchangeable sodium on the exchange complex is primarily responsible for the pH increase on dilution, but it is significant that the hydrolytic pH is approximately the same in all samples except in the top 6 inches of the Joseph soil. In view of the unusually low exchangeable sodium content of the Mingus soil, both good and poor, in contrast with the appreciable content of the Joseph soil (table 2), a higher hydrolytic pH value in the Joseph soil was to be expected. Here the repressive effect of sodium ions in the soil solution manifests itself. As the soluble sodium increases with depth, the hydrolytic pH value correspondingly decreases.

The high content of exchangeable magnesium evidently does not play a significant part in determining the pH value of the soils. The hydrolysis of magnesium clay is similar to that of calcium clay at corresponding moisture contents. If the tendency of magnesium clay to hydrolyze were as great as that of sodium clay, the pH values of these soils would be far higher, since the concentration of soluble magnesium is generally too low to exert an appreciable repressive effect.

Mineral composition of the colloidal clay

It has been shown by Buehrer, Robinson, and Deming (3) that the colloid fractions of southwestern desert soils are composed predominantly of montmorillonite and illite. Since the nature of the colloidal clay is important in determining the physical properties of soil, the soils of the Mingus and Joseph series were subjected to thermal and fusion analysis. As shown in table 4, the colloidal clay of these soils consists principally of montmorillonite and illite, with montmorillonite predominating over illite in the "poor" soils. Fusion analysis showed that the Mingus clay colloid contained 6 per cent nonexchangeable, that is, crystal-lattice, magnesium; and the Joseph colloid, about 3 per cent. This substitution of magnesium for aluminum in the montmorillonite lattice leaves the lattice with an excess of negative charge and manifests itself in an increase in base-exchange capacity. It also increases the tendency of montmorillonite toward swelling and dispersion, and this may account in part for the unusual degree of impermeability of these soils.

Source of the magnesium

The magnesium in these soils may have originated from the irrigation waters used since the soils were brought under cultivation and from the parent material from which the soils were formed. Analysis of Verde River water used on the Mingus soil showed it to contain only 51 ppm. magnesium and 35 of calcium.

The well water used for irrigation on the Joseph soil contained 17 ppm. magnesium and 52 of calcium. Hence the high exchangeable and nonexchangeable magnesium content of these soils can hardly be attributed to the water used for irrigation.

A group of samples of parent limestone collected from the field where the unproductive Mingus soil occurs was found to contain amounts of MgO ranging from a trace to 12 per cent. Magnesian limestones generally range between 5 and 15 per cent MgO. Nine shale samples from the general region where the Joseph

TABLE 3
Water-soluble salt content and pH values of Mingus and Joseph soils
Salt and ion contents on dry-soil basis

SOIL	DEPTH	TOTAL SALT CONTENT	CATIONS			ANIONS				pH VALUES		
			Ca	Mg	Na	Cl	SO ₄	CO ₃	HCO ₃	Soil paste	1:10 dilution	Hydro- lytic
	<i>inches</i>	<i>ppm.</i>	<i>ppm.</i>	<i>ppm.</i>	<i>ppm.</i>	<i>ppm.</i>	<i>ppm.</i>	<i>ppm.</i>	<i>ppm.</i>			
Mingus (poor)	0-6	1,171	105	85	78	73	156	0	674	7.90	8.60	0.70
	6-18	1,052	85	80	90	77	90	0	620	7.90	8.65	0.75
	18-30	1,007	55	90	106	61	82	0	623	8.00	8.85	0.85
	30-48	1,135	55	100	119	65	164	0	622	8.00	8.75	0.75
	48-66	1,325	65	130	140	74	300	0	610	8.00	8.70	0.70
Mingus (good)	0-6	895	100	65	50	70	0	0	610	7.85	8.50	0.65
	6-18	694	90	30	39	57	0	0	478	7.90	8.50	0.65
	18-30	719	90	45	46	62	0	0	476	7.80	8.60	0.80
	30-48	709	90	50	50	58	0	0	461	7.80	8.65	0.85
	48-66	814	200	5	50	72	0	0	492	7.85	8.55	0.70
Joseph (poor)	0-2	2,591	218	8	99	1160	576	0	530	7.65	8.70	1.05
	2-6	3,099	147	0	248	1140	724	0	635	7.80	9.10	1.30
	6-16	9,963	679	192	1207	2910	4505	0	470	7.60	8.50	0.90
	16-26	18,815	1178	424	1632	6436	8847	0	340	7.60	8.45	0.75
	26-72	32,102	3488	913	1954	7800	17592	0	365	7.70	8.30	0.60
	72-102	30,694	3582	902	1772	6850	17118	0	470	7.80	8.20	0.40

soil occurs ranged from 0.8 to 3 per cent MgO. Shales generally contain up to 5 per cent MgO. It therefore appears probable that the magnesium status of these soils bears a close genetic relation to the rocks occurring in the vicinity of these areas.

EFFECT OF MAGNESIUM AND OTHER EXCHANGEABLE BASES ON PHYSICAL PROPERTIES OF SOILS

To evaluate the effect, upon soil structure, of magnesium present in the exchange complex, data were obtained on capillary rise, moisture equivalent, and capillary and noncapillary porosity of several soils saturated with magnesium and other exchangeable bases. Because of their extremely high clay content, the Mingus and Joseph soils were not used in this study. Instead, Mohave clay

TABLE 4

Mineral composition of the colloidal clay of Mingus and Joseph soils

	DEPTH	K ₂ O	MgO	BASE-EX-CHANGE CAPACITY	CRYSTAL-LATTICE H ₂ O*	MINERAL COMPOSITION†		
						Kao-linite	Mont-morillonite	Illite
	<i>inches</i>	<i>per cent</i>	<i>per cent</i>	<i>me./100 gm.</i>	<i>per cent</i>	<i>per cent</i>	<i>per cent</i>	<i>per cent</i>
Mingus (poor)	0-6	2.69	6.15	80.3	5.89	3	64	45
	30-48	2.61	5.97	80.2	5.64	0	67	44
Mingus (good)	0-6	2.76	5.71	75.6	5.70	5	55	46
	48-66	2.81	6.07	58.5	5.82	6	52	47
Joseph (poor)	0-2	2.34	2.52	86.3	6.52	6	74	39
	30-72	2.78	3.20	84.2	6.08	2	70	46

* By ignition between 300 and 1,000°C.

† Calculated on the basis of the following selected average values for the standard minerals: Montmorillonite: K₂O, none; base-exchange capacity, 100 me./100 gm.; crystal-lattice water, 5 per cent. Illite: K₂O, 6 per cent; base-exchange capacity, 30 me./100 gm.; crystal-lattice water 5 per cent. Kaolinite: K₂O, None; base-exchange capacity 10 me./100 gm.; crystal-lattice water, 14 per cent.

TABLE 5

Comparative physical measurements on Casa Grande loam and Mohave clay loam saturated with different bases

	ORIGINAL SOIL	SOIL SATURATED WITH EXCHANGEABLE			
		H	Na	Mg	Ca
<i>Capillary rise, cm./20 hr.</i>					
Casa Grande loam.....	30.8	50.9	1.0	37.1	34.9
Mohave clay loam.....	—	—	2.2	37.6	35.7
<i>Moisture equivalent, per cent</i>					
Casa Grande loam.....	19.6	19.6	45.4	21.9	22.9
Mohave clay loam....	—	—	28.4	20.7	21.5
<i>Noncapillary porosity, per cent</i>					
Casa Grande loam.....	12.8	26.5	2.5	23.7	29.8
<i>Capillary porosity, per cent</i>					
Casa Grande loam.....	87.2	73.5	97.5	76.8	70.2

loam, Casa Grande loam, and Gila fine sandy loam were chosen. Results with the Casa Grande and Mohave soils, in table 5, show that the magnesium-saturated soils behaved much like the same soils saturated with calcium, and not at all like

the sodium-saturated soils. The sodium-saturated soils show a significantly higher moisture equivalent and lower capillary rise than either the calcium- or the magnesium-saturated soils. These results are in agreement with those of Anderson (1) and Eaton and Horton (4). They suggest that magnesium ion in the exchange complex is not responsible for the unfavorable physical condition of these soils.

It has been suggested that magnesium may act differently under different pH conditions or in the presence of other cations. Accordingly capillary rise determinations were made on samples of Gila fine sandy loam saturated with H, Ca,

TABLE 6
Capillary rise measurements on Gila fine sandy loam saturated with different bases

BASE-SATURATION* OF SOIL				CAPILLARY RISE cm./20 hrs.
H	Ca	Mg	Na	
0	0	100	0	39.3
0	0	80	20	22.7
0	0	50	50	13.8
0	0	20	80	13.5
0	0	0	100	13.8
0	100	0	0	43.7
0	80	0	20	28.4
0	50	0	50	17.4
0	20	0	80	14.8
0	25	25	50	18.8
0	20	80	0	37.9
0	40	60	0	33.9
0	50	50	0	36.6
0	60	40	0	37.9
100	0	0	0	45.9
80	0	20	0	43.3
60	0	40	0	43.1
50	0	50	0	42.7
40	0	60	0	42.0

* Amounts of exchangeable bases expressed as percentage of total base-exchange capacity.

Mg, and Na in various definite proportions. These samples were prepared by mixing amounts of soil fully saturated with a single cation in such proportions as to give a mixture of known composition with respect to the exchangeable cations. The pH values of the Gila fine sandy loam samples used, as measured on the soil paste, were as follows: H-saturated, 4.15; Ca-saturated, 7.40; Mg-saturated, 8.35; Na-saturated, 9.85.

The results of this experiment are shown in table 6. Here again, magnesium in the exchange complex behaves more like calcium, in its effects on physical prop-

erties of the soil, than like any other of the cations studied. The capillary rise of the 100 per cent magnesium-saturated soil was 39 cm./20 hours, and that of the 100 per cent calcium-saturated, 43.7 cm. In mixtures of calcium and magnesium, the capillary rise was substantially constant at 37 cm. over the entire range of compositions. Sodium invariably decreased the magnitude of the rise, whereas hydrogen increased it.

If capillary rise is a measure of structural condition in a soil, it is evident that the high percentage of magnesium present in exchangeable form is not responsible for the poor structure and impermeability of the Mingus and Joseph soils.

DISCUSSION

The experimental evidence presented in this paper has led to the conclusion that in its effect upon the structural properties of a soil, magnesium acts like calcium and not, as has been held by some investigators, like sodium. For this reason a high content of exchangeable magnesium may not be the fundamental cause of poor structural condition and of low productivity of some field soils.

In the Hawaiian Islands it has long been recognized that a soil high in replaceable magnesium may lead to difficulties. Working on the cause of poor stands of sugar cane in certain fields, Hance and Stewart (6) found that "the good soils had a lower content of magnesium than was found on the adjoining poor soil." In pot experiments to determine whether magnesium toxicity was involved, they found that the soil in the magnesium-treated pots had undergone notable change in structure and had become rubbery and impermeable. The roots in the soil containing a high amount of replaceable magnesium were stunted and deficient in secondary roots. These symptoms are strikingly similar to those associated with high-sodium soils.

Joffe and Zimmerman (8) also worked on the exchangeable magnesium problem, using plant growth as a criterion of the effect of magnesium. In pot experiments with sudan grass on soils of different Ca:Mg, Ca:Na, and Mg:Na ratios, they concluded that "if [exchangeable] magnesium is present in high concentration, its effects are harmful and tend in the same direction as sodium." A low Ca:Mg ratio, therefore, would cause a soil to behave like one high in replaceable sodium.

Anderson (1), on the other hand, has shown that in respect to water sorption, heat of wetting, swelling, moisture equivalent, Zeta potential, and pH, soils saturated with Mg behave more nearly like Ca-saturated than Na-saturated soils. Eaton and Horton (4) similarly found, in work on the moisture equivalents of 12 soils wet with either distilled water or 0.02 *N* electrolyte, that the values for the Ca-saturated and Mg-saturated soils were practically identical and were much lower in magnitude (frequently one-half) than the corresponding values for the Na-saturated soil.

This similarity in behavior between exchangeable calcium and magnesium was further shown by Buehrer and Rose (2) in connection with the phenomenon of water binding as a result of puddling of Pima clay saturated with different cations. These workers found that the number of mols of water "bound" per gram-ion of cation was the same for the Ca- and Mg-saturated soils and about twice

that of the Na-saturated soil. Since calcium and magnesium ions have virtually identical ionic hydration and electric potential and their values are at least as great as those for sodium, it is reasonable to conclude that they should be similar in their effects on soil properties. Only at the moisture equivalent did the puddled Mg- and Na-saturated soils show similarity in their ability to bind water.

The similarity in behavior of Ca- and Mg-soils is further shown by the experiments on capillary rise in the present investigation. In contrast with the reputed lack of structure of high-magnesium soils in the field, these experiments showed that a soil completely saturated with magnesium was aggregated and friable.

The poor Mingus and the exceedingly impervious Joseph clay are soils of unusually heavy texture down to a considerable depth in the profile (66 inches in the Mingus and 102 inches in the Joseph). As a result of the poor internal drainage, there has been a progressive build-up of salinity. In addition, the colloidal clay fraction of these soils shows a preponderance of montmorillonite, a condition in desert soils associated with poor structure and great ease of dispersion. Either of these conditions is of such magnitude in these soils as to completely overshadow the high-magnesium status.

A laboratory experiment was carried out to determine whether a soil like Mingus clay could be reclaimed by the use of gypsum. Columns of the soil were treated with solutions of CaCl_2 and CaSO_4 as well as by incorporation of granular gypsum at the rate of 2 and 4 tons per acre, and their percolation rates determined. No improvement in percolation rate could be observed. This observation confirms the previous finding that calcium and magnesium are so closely similar in their effect on the physical properties of the soil that replacement of the magnesium by calcium would fail to bring about flocculation or aggregation and would not result in improved permeability to water.

The cause of the low productivity of these soils is, therefore, not the high degree of magnesium saturation in the exchange complex but, rather, the unusually heavy texture, high content of montmorillonite in the colloidal clay fraction, and resultant poor internal drainage and accumulation of soluble salts in toxic concentrations. It is a question whether such soils can be economically reclaimed. The only rational use to which they can be put is to grow shallow-rooted small-grain crops, with an occasional flash irrigation, not sufficient to cause waterlogging, and an occasional fallow after deep-plowing to give the clay colloids an opportunity to become at least partly dehydrated. An additional procedure would be to withhold irrigation water during the latter part of the growing season. This would cause the plant roots to withdraw moisture from the lower horizons and thus effect partial dehydration. If such partial dehydration can be effected and organic matter incorporated to promote aggregation, the soil should be heavily irrigated to remove the accumulated salts.

SUMMARY

A study has been made of two soils of northern Arizona which in recent years have become unproductive as a result of poor structural condition, restricted water penetration, and high salt accumulation. An unusual feature of these soils

is their high native content of exchangeable magnesium. Both soils are of heavy texture, ranging from 35 to 75 per cent clay. They are mildly alkaline. Soluble salts range from 700 to 1,300 ppm. in one of the soils and between 2,600 and 32,000 ppm. at 6 feet in the other. The mineral composition of the colloidal clay was found to range from 60 to 70 per cent montmorillonite, and from 30 to 40 per cent illite, which accounts in part for the high degree of swelling and poor water penetration of the soils.

The magnesium in these soils was traced primarily to high magnesium-bearing limestones and shales from which the soils were derived, and in much lesser degree to the irrigation water used.

An independent study on three different productive soils from southern Arizona saturated with calcium, magnesium, sodium, and hydrogen, respectively, was made by measuring moisture equivalent, capillary rise, and capillary and noncapillary porosity. The Mg-saturated soils gave results more nearly identical with those saturated with Ca than with Na. Moreover, the soils saturated with Mg did not exhibit poor physical condition.

It is concluded that the low productivity of these high-Mg soils is not due to their high exchangeable Mg content, but rather to their heavy texture and the high montmorillonite content of the colloidal clay, which in turn are responsible for poor structure and lack of internal drainage.

REFERENCES

- (1) ANDERSON, M. S. 1929 The influence of substituted cations on the properties of soil colloids. *Jour. Agr. Res.* 38: 565-584.
- (2) BUEHRER, T. F., AND ROSE, M. S. 1943 Studies in soil structure: V. *Ariz. Agr. Exp. Sta. Tech. Bul.* 100: 155-218.
- (3) BUEHRER, T. F., ROBINSON, D. O., AND DEMING, J. M. The mineral composition of the colloidal clay fraction of some Southwestern soils in relation to field behavior. *Soil Sci. Soc. Amer. Proc.* (1948) 13. (In print.)
- (4) EATON, F. M., AND HORTON, C. R. 1940 Effect of exchange sodium on moisture equivalent and on the wilting coefficient of soils. *Jour. Agr. Res.* 61: 401-425.
- (5) GARDNER, R. 1945 Some soil properties related to the sodium salt problem in some irrigated soils. *U. S. Dept. Agr. Tech. Bul.* 902.
- (6) HANCE, F. E., AND STEWART, G. R. 1927 Replaceable bases in the soils of central Hawaii. *Hawaii. Planters' Rec.* 31: 342-361.
- (7) HENDRICKS, S. B., AND ALEXANDER, L. T. 1939 Minerals present in soil colloids: I. *Soil Sci.* 48: 257-271.
- (8) JOFFE, J. S., AND ZIMMERMAN, M. 1945 Sodium, calcium, and magnesium ratios in the exchange complex. *Soil Sci. Soc. Amer. Proc.* (1944) 9: 51-55.
- (9) KELLEY, W. P. 1934 The so-called solonetz soils of California and their relation to alkali soils. *Amer. Soil Survey Assoc. Bul.* 15: 45-52.
- (10) RIECKEN, F. F. 1945 Some considerations in the magnesium cycle of weathering in solonetz soils. *Soil Sci. Soc. Amer. Proc.* (1944) 9: 391-395.
- (11) SHAVRYGIN, P. I. 1935 The influence of adsorbed magnesium on the physical properties of the soil. *Pedology [U.S.S.R.]* 30: 167-173. [Original not seen. Abstract in *Chem. Abs.* 30: 1486. 1936.]
- (12) SHUSKO, S. Y. 1933 The role of adsorbed magnesium in the formation of solonetz properties in soils. *Chemization Socialistic Agr. [U.S.S.R.]* 3: 217-220. [Original not seen. Abstract in *Chem. Abs.* 27: 545. 1933.]

MAINTENANCE OF SOIL ORGANIC MATTER: I. INORGANIC SOIL COLLOID AS A FACTOR IN RETENTION OF CARBON DURING FORMATION OF HUMUS

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Maintenance of soil organic matter at a satisfactory level in cultivated soils is generally recognized as one of the major problems of agriculture. The supply of carbonaceous materials is limited and most of these materials are oxidized rather rapidly. Active or readily decomposable forms of organic matter, well supplied with nitrogen, are usually best, but under some conditions relatively inert materials, such as peat, serve as fair substitutes. The suitability of different organic materials as humus sources, their rates of decay under a variety of conditions, and the quantities of residual material left after various periods are not always well understood. There is also some doubt as to the effect of the addition of undecomposed plant materials upon the native soil organic matter. The present series of papers deals with these subjects.

The first paper considers the method used for determining organic carbon and gives data on the effect of soil colloids upon the rate of disappearance of various kinds of plant materials during the process of decay in sand, in sand-colloid mixtures, and in soil.

MATERIALS AND METHODS

The general procedure followed was to add various types of materials in a finely ground, air-dry condition to 100 or 200 gm. of soil, sand, or sand-colloid mixture in 250- or 400-ml. beakers. The composition of the organic materials is shown in table 1. The rates of addition were at 0.3 to 1.5 per cent carbon. In some cases, shown in the tables, 1 per cent finely powdered calcium carbonate was added. Urea was also supplied where necessary to lower the carbon-nitrogen ratio to either 10 to 1 or 15 to 1. A neutral mixture of monopotassium and dipotassium phosphate was added in all cases in amounts equivalent to 300 pounds of P_2O_5 and 200 pounds of K_2O per 2,000,000 pounds of sand or soil. This amount ensured an adequate supply of the two essential mineral elements without appreciably affecting the reaction.

Cecil clay loam, used in some experiments, was from the 6-14-inch depth and had a pH of 4.9. Mohave clay loam was from the surface 6-inch layer and had a pH of 5.5. Kaolin, which was used as purchased, had a pH of approximately 7. Calcium bentonite, prepared from sodium bentonite, had a pH of about 6.5. Carrington colloid was prepared from Carrington loam, C horizon, according to the method of Brown and Byers (3).

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After the carbon sources were thoroughly mixed with soil or sand and the moisture content was brought to optimum, the beakers were covered with watch glasses and allowed to incubate at 28°C. for the desired period. To ensure the presence of a normal soil flora, the sand and sand-colloid treatments were inoculated with soil infusion from a fertile soil. Additional moisture was added at weekly intervals to restore that lost by evaporation. Except in one experiment mentioned later, the soils were not disturbed during incubation. In the experiments reported in tables 4 to 9 duplicate samples were not incubated, but some of the data are the average of duplicate analyses of a single sample; in table 10 all treatments were run in pairs, and the results are mean values.

Since there is no entirely satisfactory chemical method for measuring availability of organic matter in soil (25), or quantity of true humus formed, it has been necessary to rely upon total residual carbon present after various intervals

TABLE 1
Composition of various organic materials

	CARBON	NITROGEN	CARBON-NITRO- GEN RATIO	LIGNIN
	<i>per cent</i>	<i>per cent</i>		<i>per cent</i>
Casein.....	47.9	15.6	3.1	—
Green oats	39.3	3.7	10.6	4.9
Wheat straw	43.1	0.6	73.0	16.4
Cellulose	44.4	—	—	—
Pine sawdust.....	48.3	Trace	—	25.8
Peat*.....	50.6	1.8	27.5	51.0
Fungus mycelium.....	52.5	2.4	21.9	24.0
Soybean plants.....	42.6	2.8	15.0	9.7
Corn stover.....	44.0	0.4	102.4	15.1

* A reed and sedge peat from Capac, Michigan.

as a measure of the changes occurring during decay. For the purpose of these studies the total carbon method is reasonably adequate and, in fact, has certain advantages over any method involving the determination of fractions only of the decomposing material. In this connection the paper of Peavy and Norman (19) is of interest. These workers determined the value of oxidative procedures for following changes in the composition of decomposing organic materials and concluded that these methods give little information on the quantity of humus formed but may furnish some information on its nature.

Analyses for total organic carbon were made by a wet combustion method using the oxidizing mixture of Van Slyke and Folch (23) and an apparatus similar to that of McCready and Hassid (16). Since this method had not been used for soil analysis, considerable preliminary work was done with it to establish its accuracy and some of the details of analytical procedure. These results are given in the following section.

EXPERIMENTAL RESULTS

Tests of accuracy of wet combustion procedure for total carbon determination in soils

Several wet combustion methods for determining carbon in soil, plant materials, pure organic compounds, and miscellaneous substances have been proposed, but only one that uses the Van Slyke and Folch (23) digestion mixture, which is composed of fuming sulfuric, phosphoric, chromic, and iodic acids, yields reliable quantitative results. These authors, as well as McCready and Hassid (16), obtained quantitative yields of CO_2 from all organic materials studied within a digestion time of 1 to 3 minutes. High accuracy is apparently due to the ability of iodic acid to oxidize CO to CO_2 .

In testing the accuracy of the digestion mixture on soil and plant samples both the manometric method of Van Slyke and Folch and the gravimetric method

TABLE 2

Comparison of the carbon content of various materials as obtained by the gravimetric and manometric wet combustion methods

MATERIAL ANALYZED	CARBON BY GRAVIMETRIC METHOD	CARBON BY MANOMETRIC METHOD	THEORETICAL CARBON
	<i>per cent</i>	<i>per cent</i>	<i>per cent</i>
Benzoic acid.....	68.87	—	68.85
Electrode carbon.....	100.20	—	100.00
Mohave clay loam.....	0.313	0.313	—
Cecil clay loam.....	0.409	0.405	—
Sand plus sawdust.....	0.287	0.280	—
Kaolin plus straw.....	0.112	0.114	—
Dry green oats.....	38.96	39.07	—
Fungus mycelium.....	52.58	52.43	—
Sawdust.....	48.09	48.17	—

of McCready and Hassid were used. In later work the gravimetric method was used exclusively. Typical results, given in table 2, show no difference in accuracy between the two procedures, as was to be expected, since the digestion mixture was the same in both cases. The analysis of benzoic acid agreed with the theoretical value. Even elemental carbon was completely converted into CO_2 by the digestion mixture. Determination of carbon in a material such as ground carbon electrodes is, however, very difficult because particles less than 60 mesh in size tend to float. Any charcoal present in soils would be determined by this method just as in the case of the dry combustion procedure.

The wet combustion method works best on low-carbon soils where the presence of much inert material checks the reaction rate. Ordinarily, soil samples weighing 1 to 2.5 gm. are used, depending on their estimated carbon content. The accuracy is greatest if the samples yield at least 25 mgm. of CO_2 . Like charcoal, dried ground plant materials tend to float on the combustion liquid and thus escape complete burning. Such materials can best be analyzed by mixing the weighed

sample in the digestion flask with about a gram of finely ground carbon-free quartz sand prior to mixing with the KIO_3 . Great caution is needed in applying heat to samples high in carbon.

The procedure as described (16) gives the total carbon content. If organic carbon only is desired, any carbonates present must be removed prior to analysis, or a separate analysis must be made for carbonates and this value subtracted from the total. In the present studies, carbonates were removed by treating the weighed sample of soil with 2 ml. of 1:9 HCl followed by gentle boiling for about 30 seconds. After cooling, an addition of NH_4OH equivalent to the 2 ml. of HCl was made, and the sample dried in an oven. Such a sample contains considerable chloride that would be absorbed during the analysis and weighed up as CO_2 unless removed. Removal is accomplished by passing the gases through a tube

TABLE 3

Comparison of total carbon values determined by the wet digestion method and the dry combustion method

SOURCE OF SOIL	WET METHOD		DRY METHOD	
	Total carbon	Total organic carbon	Total carbon	Total organic carbon
	<i>per cent</i>	<i>per cent</i>	<i>per cent</i>	<i>per cent</i>
D3620 Nebraska	0.881	—	0.88*	—
D3611 Nebraska	1.434	—	1.42*	—
D 546 Oklahoma	1.341	0.789	1.36*	0.75*
9 Iowa	2.04	2.00	2.03- 2.16†	2.07†
4 Ohio	18.03	17.92	17.77-18.13†	17.82-17.91†
7 Hungary	3.16	2.22	3.04- 3.43†	2.30- 2.50†

* Analyzed by E. F. Miles.

† Analyzed by Organic Carbon Committee (4).

containing coiled silver wire heated to 425 to 475°C. in an electric furnace. The furnace is added to the absorption train following the tube containing granular zinc. The silver must be replaced from time to time to prevent clogging of the gas stream. In the absence of chlorides the hot silver wire is without effect on the determination. When soils that have been treated with HCl are analyzed the sweep of CO_2 -free air should be at a slower rate for the first 4 minutes and should be continued for a total of 10 minutes.

Table 3 gives results obtained by the wet combustion method in comparison with the dry combustion method before and after removal of carbonates. There was no significant difference in the accuracy of the two methods.

Numerous other samples of incubated soil-plant mixtures, such as reported upon below, were analyzed before and after the HCl treatment. The acid at the 1:9 concentration used had no measurable effect upon organic carbon during the 30-second heating period. Prior to these determinations there was some doubt as to the effect of the acid, since it is known (12) to attack some organic com-

pounds, such as uronic acids, when the concentration is greater and the time in contact much longer.

Humus formation in quartz sand

As a basis for comparison of the effect of colloid upon the rate of decay of plant materials, and on the quantity of residual carbon, an experiment in quartz sand was conducted. The results of these studies are shown in table 4. In the majority of the treatments 0.3 per cent carbon was added, but another series was also included in which a fivefold carbon addition was made. It should be stressed that at the lower rate of addition of carbon the quantity remaining after several

TABLE 4

Organic carbon retention in quartz sand following addition of various carbon sources

TREATMENT	C/N RATIO OF ADDED MATERIALS	0.3 PER CENT C ADDED						1.5 PER CENT C ADDED	
		Carbon present after							
		1.5 months		4 months		12 months		1.5 months	
		Total	Added C*	Total	Added C*	Total	Added C*	Total	Added C*
		%	%	%	%	%	%	%	%
None.....		.006		.005		.009		0.006	
Casein.....	3.1	.042	12.0	.032	9.0	.039	10.0	0.143	9.1
Green oats.....	10.6	.129	41.0	.082	25.9	.063	18.0	0.627	41.4
Green oats + urea.....	10.0	.127	40.3	.074	23.0	.060	17.0	0.639	42.2
Wheat straw.....	73.0	.205	66.3	.137	44.0	.094	28.3	0.978	64.8
Wheat straw + urea ..	10.0	.155	49.7	.127	40.7	.109	33.3	1.000	66.3
Cellulose ..	—	.282	92.0	.245	80.0	.140	43.7	1.367	90.7
Cellulose + urea.....	10.0	.152	48.7	.131	42.0	.094	28.3	1.332	88.4
Pine sawdust.....	—	.280	91.3	.294	96.3	.286	92.3	1.314	87.2
Pine sawdust + urea.....	10.0	.278	90.7	.285	93.3	.269	86.7	1.327	88.1
Peat.....	27.5	.284	92.7	.288	94.3	.294	95.0	1.365	90.6
Peat + urea.....	10.0	.279	91.0	.278	91.0	.294	95.0	1.431	95.0

* Residual carbon from added organic materials exclusive of substrate.

months of decomposition is too small for extreme accuracy in determination. When half or more of the added carbon has been lost, the normal error in the determination of the residual portion may be 5 per cent, or even more in a soil the native carbon of which is much greater than the residual portion.

Where a protein (casein) was added, table 4 shows that about 90 per cent of the carbon had escaped as CO₂ within the first 6 weeks. Such a material liberates CO₂ and NH₃ very rapidly. The 10 per cent residue probably represents the portion converted into the cells of bacteria and fungi.

The carbon of green oats was not lost so readily as is commonly believed. Even in this well-aerated quartz sand 40 per cent remained after 6 weeks, 24 per cent after 4 months and 17 per cent after a year. The corresponding figures for the

wheat straw-urea mixture of the same carbon-nitrogen ratio (10:1) were 50, 41, and 33 per cent. Where urea was not added the rate of decomposition was much slower, but after a year the residual carbon was reduced to 28 per cent of that added. Cellulose plus urea liberated carbon at about the same rate as did the wheat-urea mixture. In the absence of urea, however, the rate of disappearance of cellulose was very slow. Usually less than 10 per cent of the carbon of both sawdust and peat was liberated during the year of incubation even though abundant nitrogen was added.

Comparison of the rate of decomposition after 6 weeks of the various materials added at the 0.3 and 1.5 per cent rates showed no very great differences for

TABLE 5

Organic carbon retention in quartz sand containing 10 per cent kaolin following addition of various carbon sources

TREATMENT	C/N RATIO OF ADDED MATERIALS	0.3 PER CENT C ADDED						1.5 PER CENT C ADDED	
		Carbon present after							
		1.5 months		4 months		12 months		1.5 months	
		Total	Added C	Total	Added C	Total	Added C	Total	Added C
		%	%	%	%	%	%	%	%
None.....		.009		.007		.012		0.009	
Casein.....	3.1	.060	17.0	.048	13.7	.035	7.7	0.173	11.5
Green oats.....	10.6	.100	30.3	.110	34.3	.091	26.3	0.582	38.2
Green oats + urea.....	10.0	.105	32.0	.100	31.0	.089	25.7	0.624	41.0
Wheat straw.....	73.0	.269	86.7	.208	67.0	—	—	1.092	72.2
Wheat straw + urea.....	10.0	.141	44.0	.117	36.7	.124	37.3	0.883	58.3
Cellulose.....	—	.259	83.3	.268	87.0	.204	64.0	1.394	92.2
Cellulose + urea.....	10.0	.109	33.3	.080	24.3	.065	17.7	1.325	87.7
Pine sawdust.....	—	.271	87.3	.291	94.7	.269	85.7	1.412	93.5
Pine sawdust + urea...	10.0	.267	86.0	.263	85.3	.230	72.7	1.406	93.1
Peat.....	27.5	.270	87.0	.299	97.3	.295	94.3	1.347	89.2
Peat + urea.....	10.0	.266	85.7	.283	92.0	.292	93.3	1.420	94.1

casein and green oats, but in the presence of added urea both wheat straw and cellulose showed a lower percentage of decomposition where the quantity added was larger.

Humus formation in sand-kaolin mixtures

The effect of adding 10 per cent kaolin to quartz sand upon the rate of carbon loss is shown in table 5. These results are directly comparable with those reported in table 4.

The presence of kaolin did not appreciably decrease the rate of carbon loss from most of the plant materials during the first 6 weeks; in fact, in some cases it apparently favored carbon dioxide production. After 12 months, 26 per cent of the carbon of green oats was retained where kaolin was present as compared with 17

to 18 per cent in quartz sand alone. Comparable figures for the other carbon sources were less striking, or even showed the reverse effect.

Humus formation in sand-bentonite mixtures

Table 6 gives the residual carbon figures where the substrate used was a mixture of 10 per cent bentonite with sand. When the data are compared with those in table 4, some rather striking differences are evident.

The initial stage of decomposition of green oats was only slightly less rapid in the presence of bentonite than in its absence but at the end of 12 months the

TABLE 6

Organic carbon retention in quartz sand containing 10 per cent calcium bentonite following addition of various carbon sources

TREATMENT	C/N RATIO OF ADDED MATERIALS	0.3 PER CENT C ADDED						1.5 PER CENT C ADDED	
		Carbon present after							
		1.5 months		4 months		12 months		1.5 months	
		Total	Added C	Total	Added C	Total	Added C	Total	Added C
		%	%	%	%	%	%	%	%
None . . . . .		.014		.006		.020		0.014	
Casein	3.1	.091	25.7	.076	23.3	.064	14.7	0.301	19.1
Green oats	10.6	.152	46.0	.128	40.7	.129	36.3	0.678	44.3
Green oats + urea	10.0	.144	43.3	.133	42.3	.128	36.0	0.715	46.7
Wheat straw	73.0	.221	69.0	.226	73.3	.172	50.7	1.092	71.9
Wheat straw + urea	10.0	.153	46.3	.145	46.3	.134	38.0	0.775	50.7
Cellulose	—	.275	87.0	.297	99.0	.289	89.7	1.411	93.1
Cellulose + urea	10.0	.180	55.3	.151	48.1	.156	45.3	1.054	69.3
Pine sawdust	—	.282	89.3	.291	95.0	.270	83.3	1.358	89.6
Pine sawdust + urea	10.0	.273	86.3	.278	90.7	.296	92.0	1.368	90.3
Peat	27.5	.297	94.3	.301	98.3	.310	96.7	1.438	94.9
Peat + urea	10.0	.284	90.0	.301	98.3	.299	93.0	1.460	96.4
Fungus mycelium	21.9	.215	67.0	.186	60.0	.172	50.7	0.861	56.5
Fungus mycelium + urea	10.0	.188	58.0	.188	60.7	.172	50.7	0.820	53.7

sand-bentonite mixture retained 36 per cent of the added carbon, or twice as much as in the sand alone. The carbon of casein was also slower to escape when it decomposed in the presence of bentonite; 15 per cent remained at the end of the year. The carbon retention figures for wheat straw and cellulose, where urea was added, were 38 and 45 per cent, respectively, in the presence of bentonite, and 33 and 28 per cent in its absence. Where no supplemental nitrogen was present both wheat straw and cellulose were resistant to microbial attack. Sawdust and peat likewise showed little loss of carbon both in the presence and in the absence of urea. Fungus mycelium, in this case *Cladosporium*, was rather resistant to attack; after a year, half of the carbon remained.

A general comparison of the data in table 6 with those in tables 4 and 5 em-

phasizes that both the quantity and the nature of the colloid present markedly affect the quantity of carbon, or humus, retained by the soil a year later. Kaolin had a comparatively small effect, whereas bentonite, which is primarily montmorillonite, had a marked effect in holding carbon. This cannot be attributed to degree of aeration or moisture, since there was little difference in either between the kaolin and bentonite tests. Sand alone may have been somewhat better aerated than when mixed with colloids but, as already stated, the carbon retention figures for sand and sand-kaolin are similar.

TABLE 7

Organic carbon retention in Cecil clay loam following addition of various carbon sources

TREATMENT	C/N RATIO OF ADDED MATERIALS	0.3 PER CENT C ADDED						1.5 PER CENT C ADDED	
		Carbon present after							
		1.5 months		4 months		12 months		1.5 months	
		Total	Added C	Total	Added C	Total	Added C	Total	Added C
		%	%	%	%	%	%	%	%
None.....		.431		.407		.406		0.431	
Casein.	3.1	.499	22.7	.463	18.7	.460	18.0	0.680	16.6
Green oats.....	10.6	.569	46.0	.531	41.3	.513	35.7	1.169	49.2
Green oats + urea.....	10.0	.569	46.0	.546	46.3	.527	40.3	1.143	47.5
Wheat straw.....	73.0	.613	60.7	.589	60.7	.527	40.3	1.549	74.5
Wheat straw + urea . . .	10.0	.586	51.7	.572	55.0	.521	38.3	1.172	49.4
Cellulose.....	—	.676	81.7	.637	76.6	.609	67.7	1.817	92.4
Cellulose + urea	10.0	.576	48.3	.547	46.7	.524	39.3	1.366	62.3
Pine sawdust.....	—	.697	88.7	.671	88.0	.622	72.0	1.740	87.3
Pine sawdust + urea... .	10.0	.696	88.3	.686	93.0	.639	77.7	1.665	82.3
Peat.	27.5	.703	90.7	.684	92.3	.686	93.3	1.798	91.1
Peat + urea	10.0	.700	89.7	.686	93.0	.680	91.3	1.787	90.4

Humus formation in unlimed Cecil clay loam

While the experiments discussed above were in progress, similar studies were conducted in natural soils. In table 7 results obtained with the Cecil soil are given. This soil was chosen because its predominant colloid is kaolinitic. The B horizon was used because the low carbon content allows greater accuracy in analysis.

The quantity of humified material left in the Cecil soil after 12 months was similar to that left in the sand-bentonite mixture (table 6) rather than in the sand-kaolin mixture (table 5). This is especially true for green oats, straw plus urea, and cellulose plus urea, which are the most important tests. Such results might be interpreted to indicate that the type of colloid is of little importance, contrary to the results obtained in sand-colloid mixtures. The data are not, however, adequate to justify such a conclusion. Not only was the quantity of colloid not the

same in all cases but, in addition, the Cecil soil was rather acid, and acidity is well known to decrease the rate of decay and favor the growth of fungi with a resulting increase in residual carbon. In fact, in other studies not reported here, addition of lime to this soil did markedly decrease the residual carbon values for most plant materials added.

The rate of decay of sawdust and peat was again very slow. Sawdust did, however, disappear more rapidly in the Cecil soil than in most of the artificial soil or sand tests. Three fourths of the carbon remained after a year even where nitrogen was abundant.

TABLE 8

Organic carbon retention in Mohave clay loam following addition of various carbon sources

TREATMENT	C/N RATIO OF ADDED MATERIALS	0.3 PER CENT C ADDED						1.5 PER CENT C ADDED	
		Carbon present after							
		1.5 months		4 months		12 months		1.5 months	
		Total	Added C	Total	Added C	Total	Added C	Total	Added C
		%	%	%	%	%	%	%	%
None.....		.310		.307		.298		0.310	
Casein.....	3.1	.386	25.3	.358	17.0	.343	15.0	0.604	19.6
Green oats.....	10.6	.462	50.7	.431	41.3	.411	37.7	1.061	50.1
Green oats + urea	10.0	.466	52.0	.435	42.7	.403	35.0	1.032	48.1
Wheat straw.....	73.0	.520	70.0	.450	47.7	.414	38.7	1.345	69.0
Wheat straw + urea.....	10.0	.478	56.0	.446	46.3	.428	43.3	1.101	52.7
Cellulose.....	—	.560	83.3	.508	67.0	.387	29.7	1.614	86.9
Cellulose + urea.....	10.0	.484	58.0	.416	36.3	.377	26.3	1.395	72.3
Pine sawdust....	—	.575	88.3	.540	77.7	.438	46.7	1.621	87.4
Pine sawdust + urea ..	10.0	.581	90.3	.557	83.3	.544	82.0	1.685	91.7
Peat.....	27.5	.600	96.7	.606	99.7	.584	95.3	1.713	93.5
Peat + urea.....	10.0	.592	94.0	.589	94.0	.578	93.3	1.727	94.5

Humus formation in unlimed Mohave clay loam

Table 8 gives data, similar to those reported in tables 4 to 7, for the montmorillonitic Mohave soil.

In view of the normal experimental error involved in determining residual carbon in the presence of a considerably larger amount of soil carbon, the differences between the results obtained in the Mohave soil and in the Cecil clay loam are negligible except possibly for cellulose and sawdust. The results with these two materials were erratic throughout all of the tests, possibly because cellulose decomposition is a more specialized process than decomposition of a green manure crop. The presence of an active cellulose-decomposing flora in a given soil sample and its success in gaining dominance over other organisms are likely to be important.

Humus formation in limed Mohave clay loam

Addition of 1 per cent calcium carbonate to Mohave clay loam had the effect of significantly accelerating decomposition, as shown by comparison of the data in tables 8 and 9. The residual carbonaceous material after a year is usually somewhat, but not markedly, less where limed.

The Mohave soil apparently had a good flora for decomposition of sawdust, since as much as 58 per cent of the carbon was liberated as carbon dioxide in 1 year. In both the limed and unlimed soils decomposition was considerably greater

TABLE 9

Organic carbon retention in limed Mohave clay loam following addition of various carbon sources

TREATMENT	C/N RATIO OF ADDED MATERIALS	0.3 PER CENT C ADDED						1.5 PER CENT C ADDED	
		Carbon present after							
		1.5 months		4 months		12 months		1.5 months	
		Total	Added C	Total	Added C	Total	Added C	Total	Added C
		%	%	%	%	%	%	%	%
None.....		.306		.294		.283		0.306	
Casein.....	3.1	.362	18.7	.342	16.0	.332	16.3	0.527	14.7
Green oats.....	10.6	.437	43.7	.420	42.0	.376	31.0	0.992	45.7
Green oats + urea.....	10.0	.437	43.7	.391	32.3	.379	32.0	0.973	44.5
Wheat straw.....	73.0	.451	48.3	.439	48.3	.374	30.3	1.310	67.0
Wheat straw + urea.....	10.0	.448	47.3	.420	42.0	.393	36.7	1.048	49.5
Cellulose.....	—	.568	87.3	.499	68.3	.365	27.3	1.575	84.6
Cellulose + urea.....	10.0	.464	52.7	.403	36.3	.361	26.0	1.184	58.5
Pine sawdust.....	—	.578	90.7	.494	66.7	.408	41.7	1.572	84.4
Pine sawdust + urea.....	10.0	.571	88.3	.552	86.0	.525	80.7	1.592	85.7
Peat.....	27.5	.591	95.0	.565	90.3	.539	85.3	1.662	90.4
Peat + urea.....	10.0	.584	92.7	.561	89.0	.550	89.0	1.659	90.2
Fungus mycelium.....	21.9	.470	54.7	.426	44.0	.409	42.0	1.104	53.2
Fungus mycelium + urea.....	10.0	.468	54.0	.418	41.3	.423	46.7	1.104	53.2

in the absence of urea than in its presence. This was noted in other instances in the Cecil soil and sand-colloid mixtures. No explanation is offered for this unexpected result. Nitrogen is known to hold carbon in some instances during the process of humus formation, but this explanation scarcely holds during the initial stages of decomposition. Available nitrogen usually accelerates carbon dioxide evolution until all of the readily attacked sources of carbon are destroyed.

Fungus mycelium was again somewhat more resistant to decomposition than was a green manure crop or wheat straw, but nearly 55 per cent of the carbon had disappeared by the end of a year. The resistance of fungal carbon to biological attack is of course of importance in nature, since considerable quantities are synthesized by the fungi that attack crop residues.

Humus formation in sand and sand-colloid mixtures

In the foregoing data, there is evidence that bentonite when added to quartz sand is more effective in holding carbon than is kaolin. Where kaolinitic and montmorillonitic soils were compared there was, on the contrary, very little difference. Table 10 gives the results of a later experiment designed to study further the effect of colloid. In this experiment half of the treatments were left unstirred, as in all previous tests, whereas the other half were stirred each week. Kaolin, bentonite, and a Carrington soil colloid were used in mixture with sand, a total of 100 gm. being used for each treatment. Soybean plants, harvested when

TABLE 10

Effect of colloid upon retention of organic carbon during decomposition of plant materials

TREATMENT	SAMPLES STIRRED			SAMPLES NOT STIRRED		
	Residual carbon after			Residual carbon after		
	3 months	6 months	12 months	3 months	6 months	12 months
	%	%	%	%	%	%
1% C added as soybean plants						
Quartz sand	.302	.228	.205	.358	.301	.200
Quartz sand + 10% calcium bentonite	.421	.363	.337	.460	.394	.393
Quartz sand + 10% Carrington soil colloid	.322	.274	.257	.367	.310	.288
Quartz sand + 10% kaolin	.301	.235	.209	.349	.281	.247
Quartz sand + 30% kaolin	.329	.268	.228	.365	.310	.274
1% C added as corn stover						
Quartz sand	.382	.266	.230	.454	.394	.296
Quartz sand + 10% calcium bentonite	.500	.483	.457	.491	.448	.435
Quartz sand + 10% Carrington soil colloid	.464	.440	.401	.447	.426	.379
Quartz sand + 10% kaolin	.364	.298	.288	.427	.341	.297
Quartz sand + 30% kaolin	.421	—	.379	.418	.388	.361

Difference required for significance between treatment means: 5 per cent level, .028; 1 per cent level, .037.

the seeds were still green, and corn stover were added at the rate of 1 per cent carbon. The soybean hay contained 2.8 per cent nitrogen and hence required no supplemental nitrogen. The corn stover treatments received sufficient urea to bring these up to the corresponding nitrogen level.

All the three colloids usually had some favorable effect on carbon retention. In the order of decreasing effects were bentonite, Carrington colloid, and kaolin. The effects of the colloids were ordinarily less marked after the initial decomposition period than after a year. In two out of four cases the presence of bentonite in sand caused an almost twofold increase in carbon retention after a year; in the other two instances the favorable effect was 47 and 60 per cent. Carrington colloid, which is a mixture of hydrous mica and montmorillonite, caused increases in carbon retention up to 74 per cent, whereas the values with 10 per cent kaolin

showed a high of 25 per cent. An increase in kaolin up to 30 per cent resulted in less carbon loss, but even this large amount produced a smaller effect than did 10 per cent bentonite. The average percentage carbon retention figures for the various substrates after 1 year were sand 23, sand plus 10 per cent kaolin 26, sand plus 30 per cent kaolin 31, sand plus 10 per cent Carrington colloid 33, and sand plus 10 per cent bentonite 41.

Stirring usually favored the loss of carbon but not markedly. There are, in fact, a few negative results. Evidently aeration was not an important factor in any of the results reported in this paper.

The rate of liberation of carbon from green soybean tops was considerably greater than from corn stover, and the quantity of humus left after 12 months was less. This occurred even though the carbon-nitrogen ratio was made the same in both cases. Evidently the more woody nature of the cornstalks was the determining factor.

DISCUSSION

The experiments reported show that the quantity and the nature of the inorganic soil colloid affect the rate of loss of carbon and the quantity of humus formed from readily decomposable plant materials. Montmorillonite produced a greater effect than did kaolin. Several workers, such as Demolon and Barbier (5), Demolon and Brigando (6), Vinokurov (24), and others mentioned below, have shown that proteins and their degradation products, including soil humus, form combinations with inorganic soil constituents, especially montmorillonite. The formation of such organic-inorganic complexes would seem to be the most probable explanation for the effect of colloid on rate of carbon loss reported in this paper. There is no complete agreement as to the exact nature of the combinations, but these evidently vary from mere mechanical mixtures (21, 22) to close unions (7, 8, 13, 17, 18, 20) that approach the nature of chemical compounds. The closeness of the bond is undoubtedly dependent upon the particular organic-inorganic complex formed. Under acid conditions, addition of certain organic materials to montmorillonitic clays lowers (8, 18) the base-exchange capacity of the clay, thus indicating a chemical reaction. Jung (14) reported that there is some evidence that the sesquioxides can form "bridge links" between humus and clays.

The organic portion of organic-inorganic complexes is usually more resistant to decomposition (9, 17) than is the uncombined organic material. Ensminger and Gieseking (9) found that this was true for a protein-montmorillonite preparation, but kaolinite, a clay mineral of low base-exchange capacity, had a negligible effect on the hydrolysis of proteins.

Ensminger and Gieseking (7) pointed out that soil organic matter has several characteristics which suggest that it should occur in combination with inorganic colloids. In clay soils it is immobile, resists oxidation, and is removed with great difficulty from the inorganic portion of the soil by chemical extractants. These workers also pointed out that the basic amino groups of soil organic matter should be able to combine with the acidic spots on the crystal lattice of a clay that has

good cation-exchange capacity. The result would be a clay crystal covered with a "network" of organic material. Their later studies, already noted, tend to bear out these ideas. Mattson (17) had previously suggested that the tendency of proteins to combine with inorganic colloids may account for the high nitrogen content of humus and of the B horizons of soils. He pointed out that "silicate of gelatin," aluminum "proteinate," and leather ("protein tannate") are very resistant to decay. In some respects these substances are comparable to clay-protein or clay-humus complexes.

In considering the effect of inorganic colloid upon the rate of humification of plant materials, Ensminger (10) reported three important findings. These are that (a) composting increased the base-exchange capacity of plant materials and the quantity taken up by montmorillonite; (b) alfalfa was sorbed to a greater extent than was straw, probably because of its higher nitrogen content; and (c) acidity favors sorption. It has frequently been shown that materials of narrow carbon-nitrogen ratios, such as alfalfa hay, often form more humus than do materials of wide ratio, such as straw. It does not follow from such a finding that the carbon-nitrogen ratio is necessarily the determining factor. Even if supplemental nitrogen is added to straw, the humus formed may still be less than from alfalfa. It is now obvious that in many cases less emphasis should be placed on the ratio and more on the composition of the plant material (percentage of lignin, hemicellulose, cellulose, protein, etc.) added and on the type and quantity of the colloid present in the soil. The well-known fact that under similar climatic and cropping conditions soil organic matter usually increases with the clay content emphasizes the importance of the inorganic colloids in holding carbon. Poor aeration in the heavy-textured soils, an explanation sometimes given, is inadequate for explaining why these soils hold more organic matter than do sandy soils. The data in table 10 emphasize this fact. Under reasonably normal soil conditions, and where waterlogging is not a problem, the oxygen supply is adequate for rapid and complete aerobic decomposition of plant materials in both sand and clay soils. This statement is based (a) on many studies, such as those of Boynton *et al.* (1, 2), showing that the oxygen content of soils in the upper foot seldom goes below 10 or 15 per cent, and (b) on many other studies, such as those of Kempner (15), showing that biological activities are seldom appreciably decreased until the oxygen content is below 5 per cent, or even 1 per cent for many organisms. Even if the oxygen percentage should decrease to zero during a wet period, any accumulation of partly oxidized products would be attacked as soon as the excess moisture had drained away.

The finding of Ensminger that acidity favors sorption also helps to explain why the carbon of added plant materials is usually held more tenaciously in acid than in neutral soils. This was true in the present studies with Mohave soil. Other factors, such as the relatively greater activity of fungi than of bacteria under acid conditions with the resulting more efficient utilization of the energy supply, may of course be even more important.

The results obtained with casein in the present studies deserve special mention. About twice as much of the carbon was retained when bentonite was added to

sand as when it was not added. Kaolin was less effective than bentonite. There was little difference, however, in the values obtained with the kaolinitic Cecil soil and with the montmorillonitic Mohave soil. The carbon retention figures after 4 months varied between 9 and 23 per cent; after a year the extremes were 8 and 18 per cent. These values are much lower than with materials such as green oats, wheat straw, soybean tops, and corn stover. This emphasizes the importance of composition of the added material. Although abundant nitrogen was present, the carbon of casein was liberated rapidly and fairly completely. The reason for the failure of montmorillonitic colloid to produce a greater effect is not known with certainty, but in light of the facts discussed above it is likely that the proportion of the added casein that entered into combination with the colloid before being hydrolyzed by microorganisms was small. The bentonite used was a near-neutral calcium bentonite, and in these experiments no attempt was made to form a protein-montmorillonite complex prior to starting the experiment. The experimental conditions, whether with soils, sand, or sand-colloid mixtures, were purposely made to resemble closely the conditions of the normal soil. In other studies, now in progress, conditions are being made more favorable for formation of organic-inorganic complexes that should prove more resistant to biological attack.

The failure of peat to show much decomposition under any conditions during a year is in agreement with other published work (11). The maximum loss of carbon was about 15 per cent in a limed Mohave soil. Pine sawdust was less resistant than was peat, but in only 3 out of 12 tests was as much as 25 per cent of the carbon lost during the year; in one case 53 per cent had disappeared. Peat, sawdust, and to a lesser extent cellulose, showed so little decomposition that the colloid had little opportunity to be a factor in carbon retention.

SUMMARY

Laboratory studies dealing with the effect of inorganic colloids on the rate of loss of carbon during decomposition of various organic materials are reported. Carbon was determined by a wet combustion method using a digestion mixture consisting of fuming sulfuric, phosphoric, chromic, and iodic acids. Data are presented showing that this method is as accurate as the dry combustion method.

The results show that the kind and the amount of colloid present in sand-colloid mixtures are important factors in determining the quantity of carbon held after decomposition has proceeded for a year. The effect of the colloid was marked where readily decomposable materials, such as green manures and straw plus urea, were added, but was not in evidence where peat, sawdust, and cellulose were applied. Montmorillonite exerted the greatest effect in holding carbon, the increase due to addition of 10 per cent bentonite to sand being nearly twofold in some instances. Kaolin showed the least effect, whereas Carrington soil colloid, which is chiefly a mixture of montmorillonite and hydrous mica, showed an intermediate effect. In one experiment, where soybeans and corn stover plus urea were added, the average percentage carbon retention figures for the various substrates after 1 year were sand 23, sand plus 10 per cent kaolin 26, sand plus

30 per cent kaolin 31, sand plus 10 per cent Carrington colloid 33, and sand plus 10 per cent bentonite 41.

Comparison of the carbon retention values in a kaolinitic soil with those in a montmorillonitic type showed no very striking differences. This may have been due in part to the higher acidity of the kaolinitic soil, which would retard decomposition. The percentage of colloids present in the soils may also have been considerably different. In comparison with quartz sand, both soils were effective in holding humus.

The experiments reported here seem to be in harmony with the results of several workers showing that certain inorganic colloids, especially montmorillonite, protect proteins and their degradation products against attack by microorganisms through formation of organic-inorganic complexes. In the present experiments the conditions were purposely made to resemble closely those found in nature, and no attempt was made to make conditions especially favorable for maximum formation of such complexes.

After 1 year of decomposition in soil or sand-colloid mixtures, approximately 34 per cent of the carbon of green oats remained in the substrate as compared with 38 per cent of the carbon of straw supplemented with nitrogen to give the same carbon-nitrogen ratio. After a similar period in sand-colloid mixtures, 28 and 38 per cent, respectively, of the carbon of green soybean plants and of corn stover was retained. Obviously the carbon of succulent green crops does not disappear so rapidly as is generally supposed. Peat was very resistant to attack, whereas sawdust and pure cellulose gave rather variable results. The carbon of casein disappeared very rapidly, but the loss was decreased by colloids.

These results emphasize the nature of the soil and the composition of the added organic materials as determining factors in the quantity of humus formed and held by a soil; the carbon-nitrogen ratio, as such, has often been overemphasized in previous studies.

REFERENCES

- (1) BOYNTON, D., AND REUTHER, W. 1939 Seasonal variations of oxygen and carbon dioxide in three different orchard soils during 1938 and its possible significance. *Proc. Amer. Soc. Hort. Sci.* 36: 1-6.
- (2) BOYNTON, D. 1941 Soils in relation to fruit growing in New York: XV. *N. Y. (Cornell) Agr. Exp. Sta. Bul.* 763: 1-43.
- (3) BROWN, I. C., AND BYERS, H. G. 1932 The fractionation, composition and hypothetical constitution of certain colloids derived from the Great Soil Groups. *U. S. Dept. Agr. Bul.* 319: 1-44.
- (4) CROWTHER, E. M. 1935 First report of the organic carbon committee. *Trans. 3rd Internatl. Cong. Soil Sci.* 1: 114-127.
- (5) DEMOLON, A., AND BARBIER, G. 1929 Conditions de formation et constitution du complexe argilo-humique des sols. *Compt. Rend. Acad. Sci. [Paris]* 188: 654-656.
- (6) DEMOLON, A., AND BRIGANDO, J. 1932 Sur la fixation des protéides par le sol. *Compt. Rend. Acad. Sci. [Paris]* 194: 311-313.
- ✓(7) ENSMINGER, L. E., AND GIESEKING, J. E. 1939 The adsorption of proteins by montmorillonitic clays. *Soil Sci.* 48: 467-473.
- ✓(8) ENSMINGER, L. E., AND GIESEKING, J. E. 1941 The absorption of proteins by montmorillonitic clays and its effect on base-exchange capacity. *Soil Sci.* 51: 125-132.

- (9) ENSMINGER, L. E., AND GIESEKING, J. E. 1942 Resistance of clay-adsorbed proteins to proteolytic hydrolysis. *Soil Sci.* 53: 205-209.
- ✓(10) ENSMINGER, L. E. 1942 Factors affecting the interaction between organic matter and montmorillonite. *Soil Sci.* 54: 191-197.
- (11) FEUSTEL, I. C., AND BYERS, H. G. 1933 The decomposition of hydrolytic peat products including ammoniated peat. *U. S. Dept. Agr. Tech. Bul.* 389: 1-32.
- (12) FULLER, W. H. 1947 Decarboxylation rate of uronic groups contained in soil organic matter, plant gums of known constitution, plant materials, and microbial products. *Soil Sci.* 64: 183-197.
- (13) GIESEKING, J. E. 1939 The mechanism of cation exchange in montmorillonite-beidelite-nonttronite type of clay minerals. *Soil Sci.* 47: 1-14.
- (14) JUNG, E. 1943 Zur Kenntnis der Ton-Humusbindung. *Bodenk. u. Pflanzenernahr.* 32: 325-336.
- (15) KEMPNER, W. 1937 The effect of oxygen tension on cellular metabolism. *Jour. Cell. and Compar. Physiol.* 10: 339-363.
- (16) MCCREADY, R. M., AND HASSID, W. Z. 1942 Semimicrodetermination of carbon using the Van Slyke-Folch oxidation mixture. *Indus. and Engin. Chem., Analyt. Ed.* 14: 525.
- (17) MATTSON, S. 1932 The laws of soil colloidal behavior: VII. *Soil Sci.* 33: 41-72.
- ✓(18) MYERS, H. E. 1937 Physicochemical reactions between organic and inorganic soil colloids as related to aggregate formation. *Soil Sci.* 44: 331-359.
- ✓(19) PEEVY, W. J., AND NORMAN, A. G. 1948 Influence of composition of plant materials on properties of the decomposed residues. *Soil Sci.* 65: 209-226.
- (20) SAEKI, H. 1939 Studies on humus-clay complexes. *Mem. Faculty Sci. and Agr. Taihoku Imp. Univ.* 25: 1-200.
- (21) SAKUN, N. E. 1942 The interaction of humate with the mineral portion of the soil. *Pedology [U.S.S.R.]* 8: 3-19.
- (22) TSCHAPEK, M. W., AND SSAKUN, N. 1944 Über die Wechselwirkung des Humats mit den mineralischen Bestandteilen des Bodens. *Kolloid Ztschr.* 107: 41-55.
- (21) VAN SLYKE, D. D., AND FOLCH, J. 1940 Manometric carbon determination. *Jour. Biol. Chem.* 136: 509-541.
- (24) VINOKUROV, M. A. 1942 The content and composition of organo-mineral gels in soils. *Pedology [U.S.S.R.]* 3-4: 73-88.
- ✓(25) WAKSMAN, S. A. 1938 What is active soil organic matter? *Trans. 2nd Comn. and Alk. Subcomm. Internat'l. Soc. Soil Sci.* 1938(A): 17-28.

ABSORPTION OF P BY SOYBEANS AND SUDAN GRASS:

II. EFFECT OF SILICATES

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The presence of large amounts of Si in the ash of certain plants has excited much speculation as to its function. The fact that plants that normally have a high Si content have been grown virtually free of this element indicates that it is not essential or is required in only very minute amounts (14). Even so, it has been demonstrated (11, 15) that silicates under certain conditions greatly aid in the growth of higher plants.

The increased plant yields obtained in certain cases from addition of silicates or colloidal silica to nutrient solutions, sand cultures, and soils have led to various suggestions as to the possible role of Si. There are at least three schools of thought on this matter. Two of them agree that Si has beneficial effects upon the P nutrition of plants but offer different suggestions as to its possible mechanism. One group (3, 10, 12) has thought that Si can perform in the plant some of the functions of P and is a means of economizing on the use of that element. Another group (1, 6, 7, 8, 13, 17, 18) has believed that increased available Si increases P assimilation by plants, either directly or indirectly. Other workers² (2, 5) have concluded that the beneficial effects of silicates on plant growth are due to improvement in soil structure. Some investigators (9, 16) have found no effect of silicates on P uptake or plant growth in their experiments.

The purpose of the present investigation was to study further the effects of silicates on the yield and absorption of P by forage crops.

EXPERIMENTAL PROCEDURES

This study was made as a part of a larger experiment in which the effects of several salts of Mg, Ca, and Na upon the yield and P content of soybeans and sudan grass were investigated. More complete description of the soils and details of the experiment are given elsewhere (4). The silicates of Mg, Ca, and Na (60-pound equivalents per 2 million pounds of soil or per acre) and finely ground olivine and serpentine (120-pound equivalents) were applied to Ottawa fine sandy loam, in pots, on which soybeans were grown as the test crop, and to field plots of Mardin silt loam which produced sudan grass. In each case the silicate treatments were factorially combined with two levels of P. The soybeans and sudan grass grew for 60 and 56 days, respectively. The oven-dry aerial parts of the plants were analyzed gravimetrically (A. O. A. C. method) for Si and colori-

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metrically for P at the end of the test; samples for P determination were also taken from the sudan grass 4 weeks after planting.

RESULTS AND DISCUSSION

Table 1 summarizes the means for the data on the yield and the Si and P contents of soybeans grown on Ottawa fine sandy loam and sudan grass grown on Mardin silt loam. Of the plants grown in the larger investigation (4) those from the untreated (check) soils and from the soils which had received applications of silicates were analyzed for Si.

When applied alone, silicates did not increase the yield of soybeans in comparison with the check treatment. A significant decrease in yield resulted from

TABLE 1

Summary of means of data on yield and Si and P content of soybeans and sudan grass

TREATMENT	SOYBEANS			SUDAN GRASS			
	Yield/pot	Si	P	Yield/plot*	Si	P	
	gm.	per cent	per cent	gm.	per cent	4 wks.	8 wks.
Check.....	21.1	0.25	0.20	72	0.42	0.24	0.33
MgSiO ₃	23.3	0.21	0.19	77	0.81	0.28	0.33
MgSiO ₃ + P†.....	27.2	0.24	0.20	160	0.68	0.29	0.27
CaSiO ₃	22.4	0.40	0.19	99	1.12	0.26	0.32
CaSiO ₃ + P†.....	25.4	0.37	0.20	184	0.96	0.25	0.30
Na ₂ SiO ₃	4.9	0.27	0.16	163	0.74	0.29	0.31
Na ₂ SiO ₃ + P†.....	10.3	0.29	0.15	266	0.66	0.29	0.26
Olivine.....	—	—	—	72	0.46	0.26	0.32
Serpentine.....	—	—	—	83	0.39	0.26	0.32
L.S.D. at P = 0.05.....	2.3	0.09	0.02	70	0.21	0.04	0.04
L.S.D. at P = 0.01.....	3.1	0.12	0.03	93	0.29	0.05	0.05

* 12.25 square feet harvested.

† 150 pounds P₂O₅ per 2 million pounds soil (soybeans) or 300 pounds P₂O₅ per acre (sudan grass), as Ca(H₂PO₄)₂.

the application of Na₂SiO₃; hydrolysis and dissolution of organic matter were observed to result from application of this salt and the alkaline soil condition was probably responsible for the poor growth. The yields given for sudan grass are for that species alone, which was separated at harvest from weed species growing on the plots. Because of this fact, differences in sudan grass yields are not stressed; they are thought, however, to represent in a general way the response of the sudan grass to the soil treatments applied.

Where the soybeans made normal growth, the percentage of P was not significantly affected by any of the silicate treatments. On the soils treated with Na₂SiO₃ the soybeans made relatively very poor growth and the concentration of P was also significantly lowered. Since, however, the yield was so adversely affected, and the concentration of Si was not significantly increased, it does not

appear that the concentration of P was low because of replacement of P in the plant by Si. The CaSiO_3 treatment increased the Si content by approximately 50 per cent, in comparison with the check, without effect on the concentration of P.

Samples of sudan grass were analyzed for P 4 weeks after planting and for Si and P at the end of the test, when the plants were 8 weeks old. At 4 weeks the percentage of P was greater in plants from the soils treated with Mg and Na silicates than in those from the check soils. By the end of the test these differences had disappeared and the P content of the plants showed no effects of silicate treatments. The application of soluble silicates greatly increased the Si concentration in the sudan grass, however; the percentage of Si was more than doubled by the CaSiO_3 treatment and was increased to a slightly lesser extent by MgSiO_3 and Na_2SiO_3 . At the end of the test the only significant effects of soil treatment upon the percentage of P were the decreases produced by application of P in combination with the silicates; here the yield was increased and the lowered concentration of P was undoubtedly due to the dilution effect of the increased growth; the percentages of Si and of Ca, K, and N (4) decreased to about the same extent as that of P in the same plants.

It appears from the data of this experiment that conclusions regarding the effects of silicates on the absorption of P by plants may vary with the age at which the plants are sampled, as well as with the type of plant and the characteristics, especially the soluble silicate and phosphate contents, of the soil upon which the plants are grown. The data from the sudan grass harvested at 4 weeks favor the idea that increased available silicates increase the assimilation of P; the data obtained from soybeans and sudan grass at the end of the test support the idea that silicates have no effect upon P uptake.

SUMMARY AND CONCLUSIONS

The silicates of Mg, Ca, and Na, and olivine and serpentine, were applied, in factorial combination with two levels of P, to two soils. Soybeans were grown on Ottawa fine sandy loam in pots, and soybeans were grown on field plots of Mardin silt loam. Plants were analyzed for Si and P. Silicates had no significant effects upon the yield of soybeans and their concentration of P. In sudan grass harvested at 4 weeks of age the concentration of P was greater in plants from soils treated with Mg and Na silicates than in those from the check soil; the differences had disappeared at 8 weeks. The Si content of soybeans was increased by CaSiO_3 ; all the silicates except olivine and serpentine resulted in highly significant increases in the Si content of the sudan grass.

REFERENCES

- (1) AKHRONEIKO, A. I. 1934 Influence of silicic acid upon the utilization by plants of phosphoric acid from various sources. *Ztschr. Pflanzenernähr., Düngung, u. Bodenk.* 34A: 340-359. [Abstract in *Chem. Abs.* 29: 874.]
- (2) BLANCK, E., SCHORSTEIN, H., AND THEMLITZ, R. 1936 The effect of calcium silicate and carbonate on the utilization of different phosphatic fertilizers. *Jour. Landw.* 84: 297-319. [Abstract in *Chem. Abs.* 31: 6706.]

- (3) BRENCHELEY, W. E., MASKELL, E. J., AND WARINGTON, K. 1927 The interrelation between silicon and other elements in plant nutrition. *Ann. Appl. Biol.* 14: 45-82. [Abstract in *Exp. Sta. Rec.* 64: 122.]
- (4) DEWAN, M. L., AND HUNTER, A. S. 1949 Absorption of P by soybeans and sudan grass: I. *Soil Sci.* 68: 401-410.
- (5) DUCHON, E. 1925 Explanation of the yield increasing action of colloidal silica in sand cultures deficient in phosphoric acid. *Ztschr. Pflanzenerndhr. u. Düngung* 4: 316-325. [Abstract in *Exp. Sta. Rec.* 54: 219.]
- (6) FISHER, R. A. 1929 A preliminary note on the effect of sodium silicate in increasing the yield of barley. *Jour. Agr. Sci.* 19: 132-139.
- (7) GILE, P. E., AND SMITH, J. G. 1925 Colloidal silica and the efficiency of phosphates. *Jour. Agr. Res.* 31: 247.
- (8) HALL, A. D., AND MORRISON, C. G. T. 1905 On the function of silica in the nutrition of cereals. *Proc. Roy. Soc. [London]* (B) 77: 455-477. [Abstract in *Exp. Sta. Rec.* 18: 125. 1906.]
- (9) HARTWELL, B. L., AND PEMBER, F. R. 1920 The effect of dicalcium silicate on an acid soil. *Soil Sci.* 10: 57-70.
- (10) LEMMERMANN, O. 1929 On the question of the silica effect. *Ztschr. Pflanzenerndhr., Düngung, u. Bodenk.* 13A: 28-39.
- (11) LIPMAN, C. B. 1938 Importance of silicon, aluminum, and chlorine for higher plants. *Soil Sci.* 45: 189-198.
- (12) LOEW, O. 1903 The physiological role of mineral nutrients in plants. *U. S. Dept. Agr. Bur. Plant Indus. Bul.* 45.
- (13) MCGEORGE, W. T., AND BREZEALE, J. F. 1924 The influence of silica, lime, and soil reaction upon the availability of phosphates in highly ferruginous soils. *Soil Sci.* 17: 463-468.
- (14) MILLER, E. C. 1938 *Plant Physiology*. McGraw-Hill Book Co., New York.
- (15) RALEIGH, G. J. 1945 Silicon in plant growth. *Soil Sci.* 60: 133-135.
- (16) SCHOLLENBERGER, C. J. 1922 Silica and silicates in relation to plant growth and composition. *Soil Sci.* 14: 347-362.
- (17) SREENIVASAN, A. 1934 The role of silicon in plant nutrition. *Current Sci.* 3: 193-197. [Abstract in *Chem. Abs.* 29: 2205.]
- (18) TOTH, S. J. 1939 The stimulating effects of silicates on plant yields in relation to anion displacement. *Soil Sci.* 47: 123-141.

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